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PLANNING SINGLE-SPAN SKYLINES

Virgil W. Binkley
Hilton H Lysons

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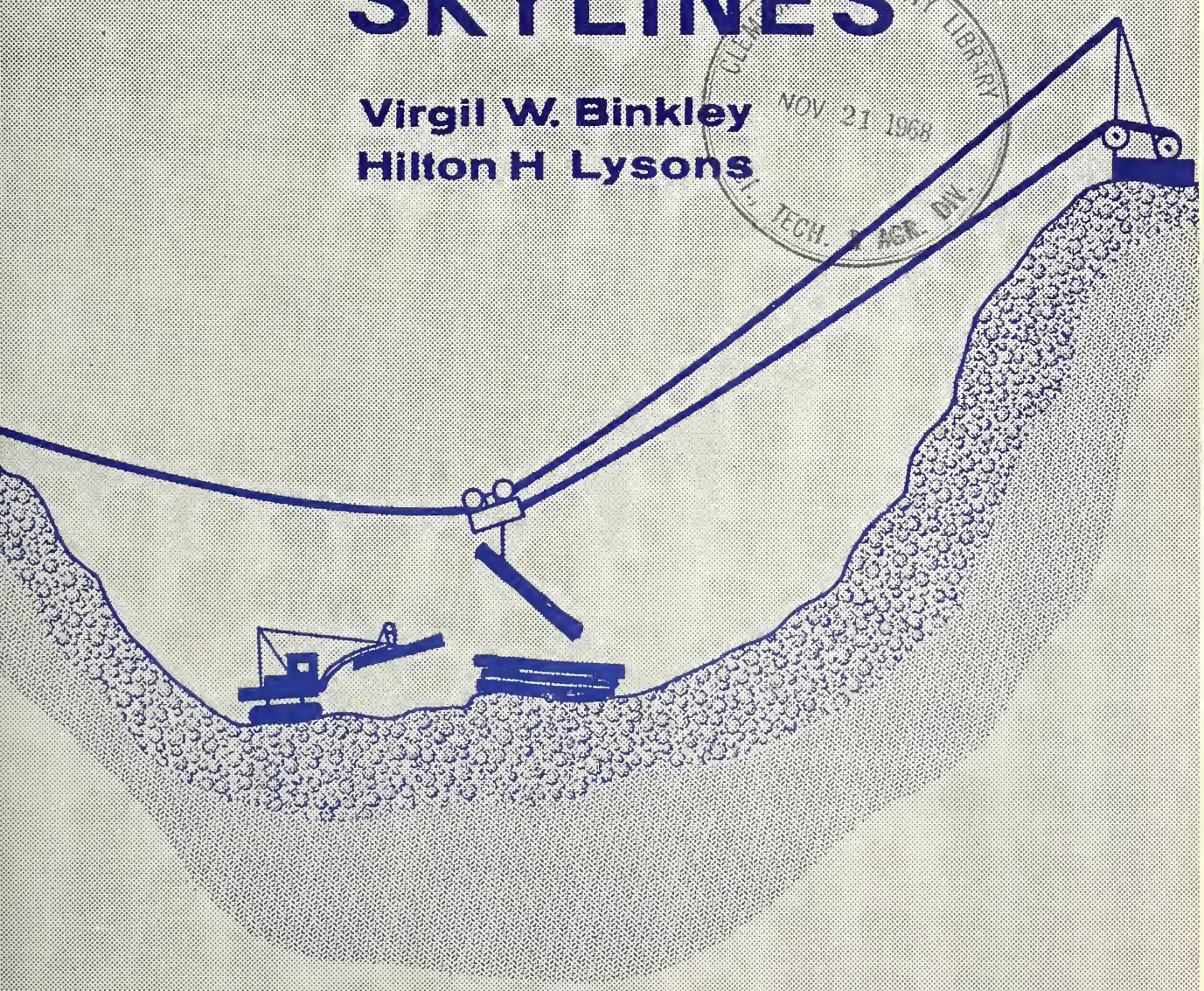

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
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PORTLAND, OREGON 1968

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1.0 INTRODUCTION

In recent years, there has been a growing demand for a yarding system that can economically transport logs from steep terrain without a dense access road network. Such a system must also be able to transport logs without disturbing sensitive soils or damaging watersheds. And in many areas, the public demands that the logged area be esthetically pleasing to the eye.

The single-span, skyline-crane yarding system is capable of yarding logs from steep terrain and meeting the above requirements if cutting units are properly designed. Numerous skyline-crane shows have been tried in the Pacific Northwest with varying degrees of success. One contributing factor to suboptimal performance has been insufficient planning of the skyline layout. To date there has been little information available to foresters, engineers, and loggers on the layout of skyline-crane operations.

It is, therefore, the purpose of this paper to provide those who have the responsibility for logging planning with the criteria for selecting areas suited to skyline-crane yarding.[1]

2.0 LOGGING PLANNING

All operations, from felling trees to unloading logs at a delivery point, must be considered when a logging plan is developed. A comprehensive plan for an entire forest area on a compartment basis should be completed before onsite location of cutting units begins. This comprehensive plan is the "blueprint" which designates each area to be harvested by the yarding equipment best suited to its terrain and to modern forestry practice. Vehicle road location must also be carefully considered in comprehensive planning so that its location is compatible with logging systems as well as other forest values.

J. Kenneth Pearce[2] has listed several factors to be considered:

> The logging planner is the 'architect' of the logging plan. To arrive at the best plan, he must consider many factors. Given the basic data on timber and topography, logging planning requires the concurrent consideration of the following factors:
>
> 1. The physical requirements of the applicable logging methods.
> 2. The most economical combination of yarding costs, road construction costs and trucking costs.
> 3. The silvicultural system and the priority sequence of cutting.
> 4. Protection of the nment stand and soil and water resources.
> 5. The safety of the men working on the landings and traveling the roads.
>
> Some of these factors may conflict. The final logging plan may be a compromise reached after weighing all factors. The relative weight to be given each factor is an administrative decision based on policy.

2.1 CRITERIA FOR SELECTING AREAS FOR SINGLE-SPAN SKYLINES

The most important objective of single-span skyline planning is to obtain adequate deflection so that the skyline has the required load-carrying capability. Deflection is defined as the vertical distance between the chord and the skyline as measured at midspan.[3]

1 A skyline-crane operation is designed to yard logs laterally to a carriage as well as to transport them either up or down a skyline to a landing. The skyline-crane should not be confused with Northbend, Southbend, or Tyler skyline yarding systems. These do not have the same lateral skidding capabilities as skyline-cranes because their butt rigging is pulled laterally by the haulback line, with a side block located adjacent to the skyline. These systems do, however, operate on single-span skylines.

2 Pearce, J. Kenneth. Forest engineering handbook. Bur. Land Manage., U.S. Dep. Interior, Oreg. State Office. 1961

3 Lysons, Hilton H., and Mann, Charles N. Skyline tension and deflection handbook. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Res. Pap. PNW-39, 41 pp., illus. 1967.

Topography is the principal contributing factor to obtaining adequate deflection.

In addition to topography, other considerations for selecting areas are: the transportation plan, log landings, skyline anchors, spar trees, and overall costs of operation.

2.1.1 SUITABLE TERRAIN

Three types of forested terrain confront the skyline planner: concave, uniform, and convex slopes. Single-span skylines are best suited to concave topography since this condition presents the least problem in obtaining adequate deflection. A concave slope with a single-span skyline is illustrated in figure 1C.

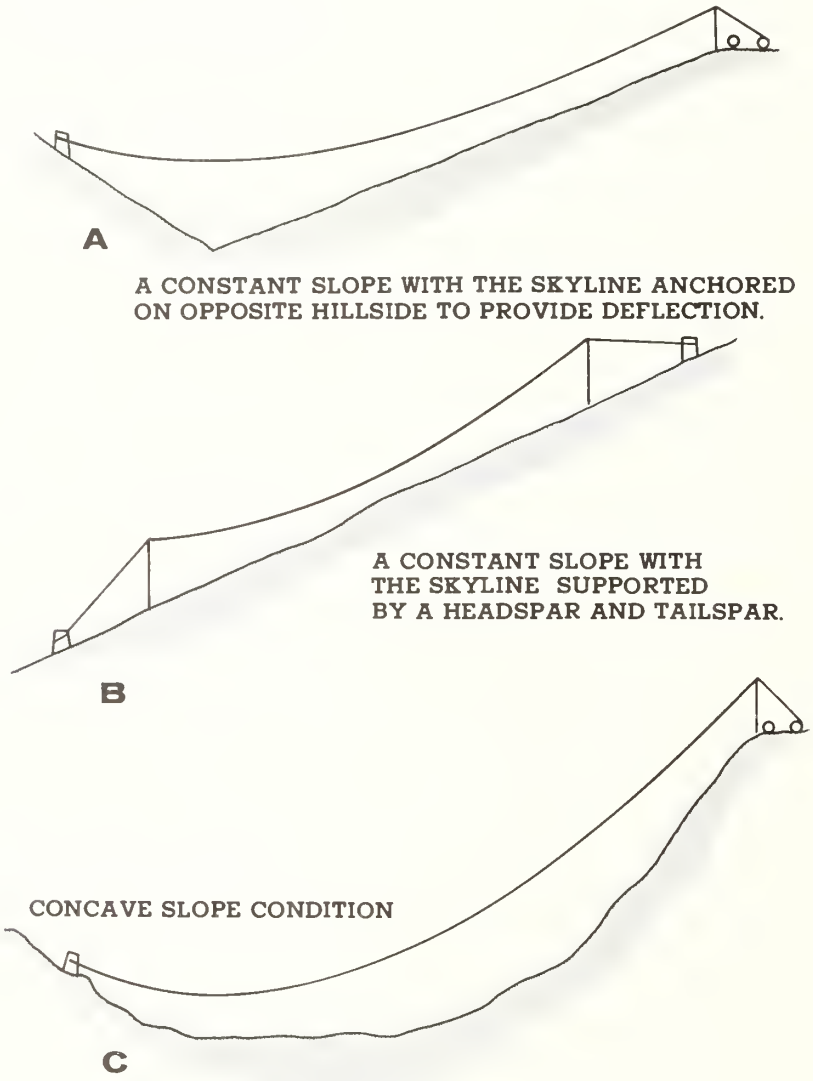
A
A CONSTANT SLOPE WITH THE SKYLINE ANCHORED ON OPPOSITE HILLSIDE TO PROVIDE DEFLECTION.
A CONSTANT SLOPE WITH THE SKYLINE SUPPORTED BY A HEADSPAR AND TAILSPAR.
B
CONCAVE SLOPE CONDITION
C
TYPICAL SINGLE-SPAN SKYLINE SETUP

Figure 1.—Typical single-span skyline setup.

Successful single-span skyline operations can also be made with constant slope conditions, although horizontal distance obtainable is usually less than with concave slope. Figure 1B shows a constant slope with the skyline supported by spar trees. Where the lower portion of a constant slope area to be yarded is adjacent to a valley or a drainage, it is frequently possible to anchor the skyline on the opposite hillside (fig. 1A), eliminating the need for a spar tree and resulting in savings of rig-up time and cost.

The convex slope condition presents the planner with the greatest difficulty, since normally it cannot be logged with a single-span skyline. The only exceptions to this are when the convex portion is part of a longer, generally concave, slope or when the convexity is so slight that spar trees can be used to overcome the problem. In cases other than these exceptions, a multi-span skyline is necessary, which introduces other problems beyond the scope of this publication.

Either of the three choices—concave, uniform, or convex terrain—directly influences the skyline length and height. The effect of this is discussed in section 2.1.6.

2.1.2 COMPATIBILITY WITH TRANSPORTATION PLAN

The overall transportation plan, including roads both built and planned, has the largest single influence on deciding whether to yard the logs uphill or downhill. In addition to the usual considerations in road planning such as construction costs, grades, soil stability, and multiple use requirements, the following log-carrying methods should be considered:

Yarding direction	*Log-carrying method*	*Soil disturbance*
Uphill	Free	None
Uphill	Drag	Slight
Downhill	Free	None
Downhill	Drag	Varies[1]

1 Soil damage varies from slight to severe, depending upon degree of slope. For moderate downhill slopes where the log drags, the disturbance is slight. However, as the slope increases, a point is reached where the log overruns the inhaul line, allowing it to swing out of control. This usually causes severe soil disturbance, damage to any residual trees, log breakage, and possible damage to the skyline carriage.

2.1.3 ADEQUATE LANDINGS

Landings for successful skyline-crane operation must include an area large enough to land logs safely and provide both storage and loading room for the logs. As a rule, the landing size for skyline-cranes is comparable to that required for high-lead logging.

Where landing space is inadequate, it may be necessary to use a rubber-tired or crawler tractor to swing the yarded logs to nearby areas for storage and loading. This added handling cost may necessitate reconsidering the location of the landing on the cutting unit.

The area where the logs are to be unhooked from the chokers should be reasonably level. This reduces the tendency of logs to roll or slide downslope.

2.1.4 ADEQUATE ANCHORS

Anchors are a basic requirement for setting up and operating skylines. They must be able to withstand the severe pull of the skyline. At present, only experience can indicate the capability of an anchor stump for a given ground condition. As a guideline, however, the following should be considered when stumps are examined for skyline anchors:

1. *Stump diameter.* — Since larger stumps are preferable, it is important to be aware of the possible lack of larger stumps at the upper end of a skyline.
2. *Stump condition.* — Stumps should be reasonably free of rot and have a sound root structure.
3. *Soil type and depth.* — Shallow soils may indicate the lack of a deep root structure.

Where these things become problems, it is often possible to obtain a satisfactory anchor by securing the skyline to several stumps. If no suitable stumps are available, a deadman, or buried logs, may be used for anchor. Sites for deadman anchors should be judged on the practicability of getting excavation equipment to the site and the depth of soil to solid rock.

2.1.5 ADEQUATE SPAR TREES

Spar trees may be required to support the skyline at one or both ends. Where spar trees are needed to provide clearance for the skyline, standing trees selected for spars should meet applicable safety code requirements.

When a headspar is required at the landing, a mobile steel spar is often used. Tailspars are usually rigged trees. Spar trees, whether they are rigged or mobile, must be located in alignment with anchor points and the landing area.

2.1.6 LENGTH AND HEIGHT OF SKYLINE

The type of terrain within the cutting unit boundaries is the major factor in determining the length of the skyline. The planner should be aware, however, that equipment limitations, access road costs, frequency of setup, yarding cycle time, and yield per acre all affect optimum skyline length. Single-span skylines have been employed in the Pacific Northwest at yarding distances up to 4,000 feet. The maximum skyline length is usually limited by either the available yarding equipment or the allowable deflection as provided by the terrain.

These same limiting factors of equipment and terrain also affect the allowable height of the skyline, which is measured from the ground to the skyline when it is loaded with only the carriage. The restricting factor in this case is the skidding line capacity of the skyline-crane carriage. Present maximums range from 100 to 400 feet of cable.

The effect of the height of the skyline above ground varies, depending on whether a "live" skyline or a "standing" skyline is used. With a live skyline, which can be raised or lowered by the yarder operator, the problem of limited skidding line capacity can be readily overcome. However, the standing skyline, which is fixed at both ends, does not have this flexibility. Thus, careful analysis by the planner is necessary to avoid exceeding the skidding line capacity.

The skidding line must be long enough to reach the ground, plus an allowance for lateral skidding.

Exact determination of skyline height can only be resolved through procedures covered below. Where this height is too great, it is necessary to change either the skyline road location or the anchor point location.

2.1.7 ECONOMICAL OPERATION

In an evaluation of the economic feasibility of a skyline-crane operation, total logging costs should be considered. Skylines are capable of transporting logs for long distances, thus reducing access road mileage and costs.

The following should be carefully considered in an evaluation of the economic feasibility of a cutting unit:

1. Conversion (the amount available for logging after minimum acceptable stumpage is subtracted from the delivered price of logs).
2. Total volume to be yarded from a cutting unit.
3. Area previously yarded within cutting unit.
4. Number of operating days per year.
5. Size of logs.
6. Skyline distance.

The cost savings of less access road construction, hauling, and road maintenance must be considered along with yarding costs when logging cost estimates are made. Skyline-crane cost analysis should include the summation of all logging costs from the stump (including felling) to delivery point.

Direct yarding costs, which include log production plus setup and takedown, may vary widely on skyline roads within a cutting unit. The decision to accept or reject a proposed cutting unit should be based on an average cost for all skyline roads within a cutting unit, rather than on the one that

appears most profitable or that has the highest cost.

Skyline yarding costs should not be compared directly with yarding costs of other systems since yarding distances for skylines may be greater. Instead, total logging costs (i.e., all costs from stump to delivery point) should be used in a comparison.

2.2 LAYOUT OF CUTTING UNITS

Once the comprehensive logging plan has been completed, layout of cutting units may be started. This phase of work is done by use of aerial photographs, topographic maps, and timber-type maps. Aerial photos in stereopairs may be used to identify preliminary landings, anchor points, and spar trees. Anchors may be located within proposed cutting units, but more often it is desirable to locate them outside a cutting unit to improve deflection or to take advantage of larger anchor stumps.

Detail identified on the photos may be transferred to a topographic map for use in laying out cutting units and skyline roads. Good-quality skyline road profiles may be plotted from topographic maps having a scale of 1 inch = 400 feet and a contour interval of 20 feet. The planner should be aware that accuracy of topographic maps in mountainous terrain may be questionable and suitable only for preliminary work pending onsite confirmation.

Accurate data on timber volume per acre and log size are needed for estimating yarding and rigging costs. Timber-type maps should also be superimposed on the topographic maps to identify more clearly where skyline roads may be located.

Figure 2 illustrates location of skyline roads in a forest area which has been laid out for single spans.

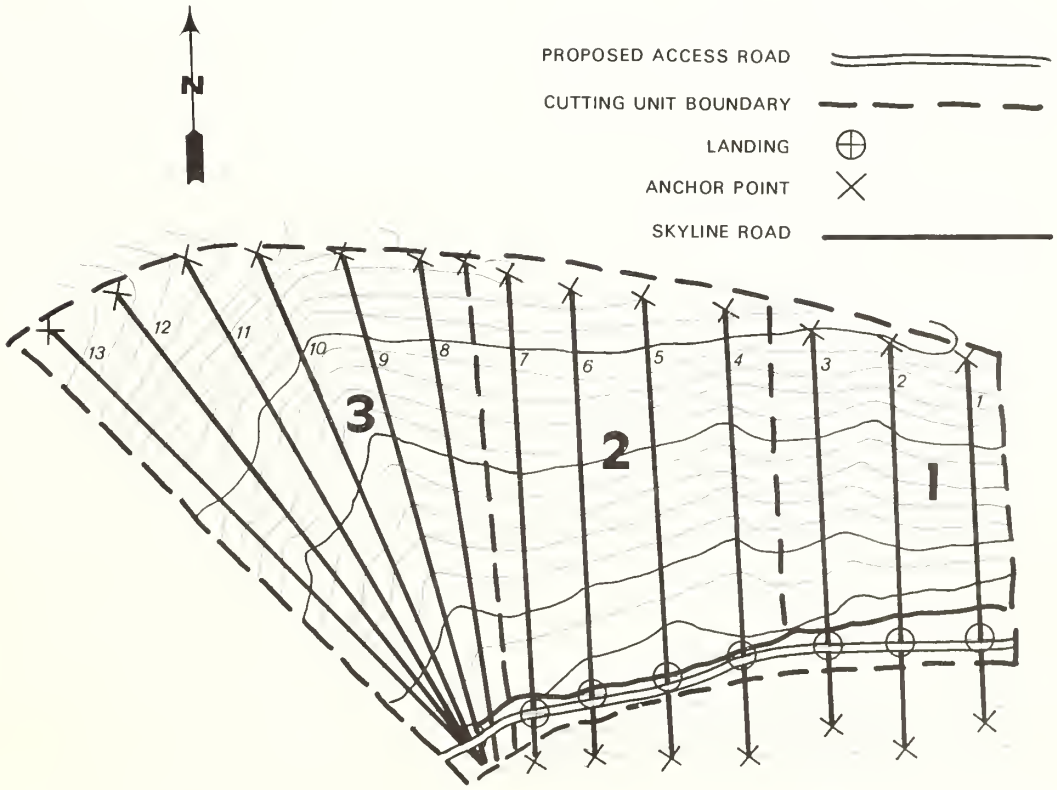

Figure 2.—Rock Mountain skyline logging plan.

2.2.1 SELECTION OF RECTANGULAR LAYOUT

Rectangular cutting units are generally laid out on hillsides where contours are reasonably straight (see fig. 2, units 1 and 2). Skyline roads in such layouts are parallel, or nearly so, depending on availability of anchors and spar trees.

This layout results in little or no lateral ground slope, thereby minimizing problems in lateral yarding of the logs.[4] Lateral ground slope occurs when the skyline crosses the contour at an angle other than 90°.

2.2.2 SELECTION OF FAN-SHAPED LAYOUT

Fan-shaped cutting units are generally laid out in areas where contour lines curve around ridge points or into drainage heads. Skyline roads in such a layout radiate from one anchor point, usually located at the landing. Cutting unit 3 in figure 2 illustrates a fan-shaped cutting unit.

2.3 LOCATE SKYLINE ROADS

Parallel skyline roads may be spaced about 300 feet apart. Spacings greater than 300 feet cause a sharp increase in cycle time. [5] Other influences on spacing are areas broken up with small creeks and ridges. Locating a skyline road down a creek should be avoided because the skidding line must then be pulled upslope on both sides of the skyline and the logs will be skidded downslope; logs will roll and cause hangups.

In partial cuts such as thinnings, road spacing is usually closer than in clearcuts. Tests in a Douglas-fir thinning operation showed that logs could be yarded from a 220-foot parallel skyline road spacing with little damage to remaining trees.[6] Road spacing distance on fan-shaped layouts is measured at the tailspar or anchor point.

4 Binkley, Virgil W. Economics and design of a radio-controlled yarding system. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Res. Pap. PNW-25, 30 pp., illus. 1965.

5 Report on administrative study of skyline logging. U.S.D.A. Forest Serv., Region 5, Klamath National Forest, Yreka, Calif., 23 pp., illus. 1966. (Also, see footnote 4.)

6 Binkley, Virgil W., and Williamson, Richard E. Thinning Douglas-fir on steep slopes. Forest Ind. 95(2): 60-61, illus. 1968.

2.3.1 PLOT PRELIMINARY SKYLINE ROAD PROFILES

When preliminary skyline roads have been located on a topographic map, profiles of these roads may be plotted with a scale of 1 inch = 100 feet for both horizontal and vertical distance.

2.3.2 DETERMINE SKYLINE LOAD-CARRYING CAPABILITY

Allowable deflection may be determined by the "chain and board" method outlined in Lysons and Mann (see footnote 3), and skyline tension and load-carrying capability may then be calculated for each profile by the use of appropriate tables and worksheets provided therein. If deflection is not adequate for transporting a minimum load, the skyline road must be relocated, which may require changing cutting unit boundaries and landing locations.

When there is little or no change in topography, it is not essential to profile each skyline road. When topography changes, make checks by plotting new profiles.

2.3.3 DETERMINE MAXIMUM ALLOWABLE SKYLINE HEIGHT ABOVE GROUND

The maximum above-ground height of a standing skyline is dependent on the skidding line capacity of the carriage. In determination of maximum height, an allowance for lateral skidding distance must also be considered. If maximum skyline height occurs at the landing, an allowance for lateral skidding may not be required. This sometimes occurs when logs are transported over ground previously yarded by another system, either as part of the current operation or prior to it.

If the height of the skyline is greater than the skidding line capacity of the carriage to be used, anchor points may have to be moved or a live skyline used instead of a standing skyline.

Skyline height above ground may be found by taking appropriate measurements from the skyline profile used in the chain and board method (see footnote 3).

2.4 PRELIMINARY LOGGING COST ANALYSIS

Before the start of onsite layout of cutting units, it is wise to make a logging cost analysis. Even though payload-carrying capability of each skyline may appear to be adequate, logging costs may be unacceptable. If cost estimates are favorable, fieldwork may be started which will provide accurate ground profiles for each skyline road.

The procedures for estimating yarding costs for skyline-crane yarding systems are complicated and beyond the scope of this document.

3.0 ONSITE LOCATION AND DESIGN OF CUTTING UNITS

When preliminary logging cost analysis shows that a particular area may be logged economically, onsite location may be started. This fieldwork and the resulting skyline road profiles are used to verify the layout made on the topographic map. The following sections, 3.1 through 3.3.4, define the major steps which should be followed in the onsite work and the final planning.

3.1 RECONNAISSANCE

Before fieldwork such as boundary and profile traverse are started, an "on-the-ground" reconnaissance is needed to verify location of the landings, anchors, and spar trees identified on the aerial photographs. This work is done with aerial photographs and topographic maps as aids. The following steps briefly outline a reconnaisance of a proposed skyline cutting unit.

3.1.1 SELECT AND MARK ANCHORS

Standing trees, selected for anchors, must be inspected for decay and firmness of the root structure. Increment cores taken from standing trees at or near stump height are good indicators of stump soundness.

If deadman anchors are to be used, access routes for excavation or drilling equipment should be available. Access to tailspars as well as to anchor location is helpful in reducing rigging cost.

3.1.2 SELECT AND MARK SPAR TREES

Standing trees which meet standards for spars are marked for refereneing in the boundary traverse. These trees may or may not be used, depending on location of skyline roads.

3.1.3 SELECT AND MARK LANDINGS

Landings should be nearly level to facilitate safe handling of logs. If possible, they should avoid heavy exeavation.

3.1.4 LOCATE AND MARK CUTTING UNIT BOUNDARIES

A cutting unit boundary for single-span skylines usually follows terrain breaks sueh as creek bottoms and ridgetops on the front and back lines. Side lines should be located no farther from the eenter line of the skyline road than the skidding line ean be pulled laterally (see footnote 4).

3.2 TRAVERSE CUTTING UNIT BOUNDARY

A cutting unit boundary traverse is needed to loeate aeeurately landings, anchors, and spars. The traverse party should follow the boundary as marked (see 3.1.4). All potential anchors, landings, and spars shonld be refereneed in the traverse notes. Staff compass and Abney surveying proeedures are satisfaetory for this work.

3.2.1 PLOT BOUNDARY TRAVERSE

When the boundary traverse is completed, field notes should be plotted on a seale of 1 inch = 100 feet. All potential landings and anchors referenced in field notes should be shown on the plan view. The plan view will also provide horizontal and vertical eontrol needed for checking skyline road profiles.

3.3 LOCATE SKYLINE ROADS

Locate skyline roads, using anchors, landings, and spars referenced on the plan view. Spacing should be carefully considered as in initial skyline road location (2.3). The bearing and distance needed for profile traversing of each skyline road may be taken from the plan view.

3.3.1 TRAVERSE SKYLINE ROAD PROFILES

A skyline road traverse is similar to the boundary traverse, but it is run as a tangent from anchor point to anchor point. The resulting field notes are used to plot the ground profile of each skyline road. Side-slope notes taken at each compass setup are useful in designing skyline roads.

In areas where there is little or no variation in topography, it may not be necessary to traverse each road, but a minimum of one profile should be run for each cutting unit. Any change in topography warrants a profile traverse.

3.3.2 PLOT SKYLINE ROAD PROFILES

Procedures for designing a skyline road profile by use of field notes are the same as a trial profile. Profile notes should also be plotted as outlined in 2.3.1, and horizontal length and difference in elevation should be checked with the cutting unit plan view. Errors in excess of allowable closure should be found and corrected. Side-slope notes may be used to move a profile laterally and take advantage of a more suitable profile—this would avoid the cost of an additional traverse. This procedure is similar to adjusting the "P" (preliminary) line of a vehicle access road.

3.3.3 DETERMINE DEFLECTION, TENSION, AND LOAD-CARRYING CAPABILITY

Once the profile has been completed, deflection and tension may be determined by procedures outlined in Lysons and Mann's handbook (see footnote 3). If deflection is adequate, cutting unit plan view and profiles may be detailed in final form. If deflection is not adequate, skyline roads must be relocated. Figure 3 illustrates a cutting unit plan view showing location of skyline roads; figures 4, 5, and 6 are profiles of these roads.

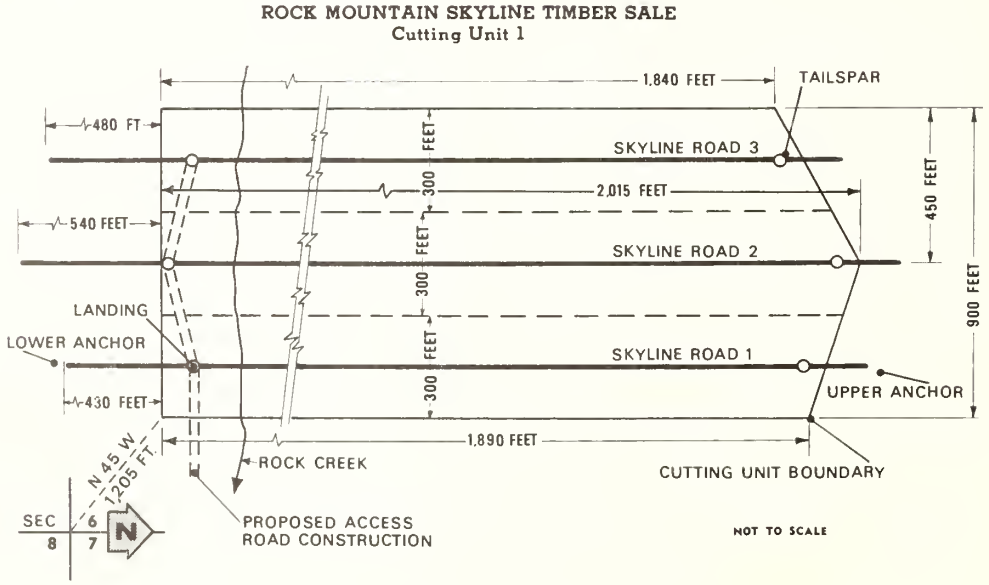

Figure 3.—Cutting unit plan showing location of skyline roads.

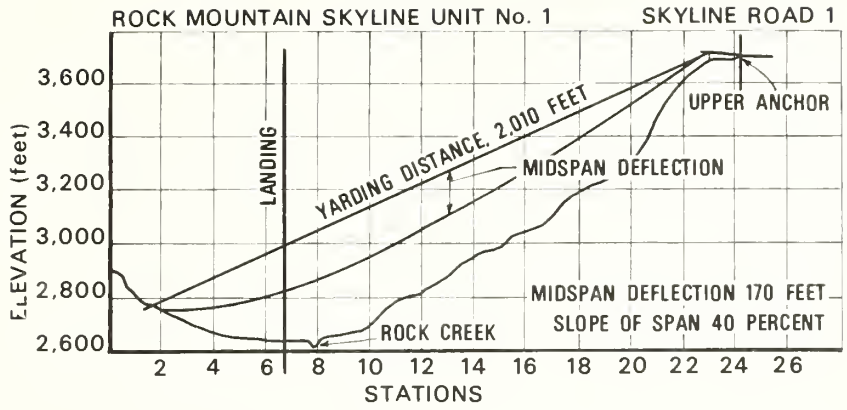

Figure 4.—Profile of skyline road 1, Rock Mountain skyline unit No. 1.

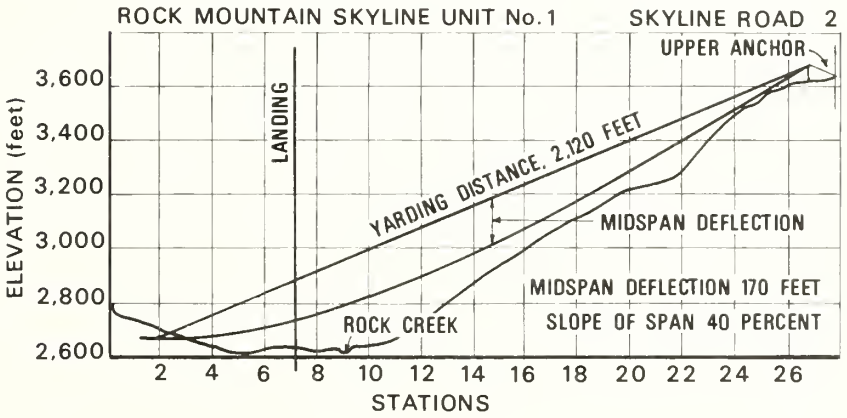

Figure 5.—Profile of skyline road 2, Rock Mountain skyline unit No. 1.

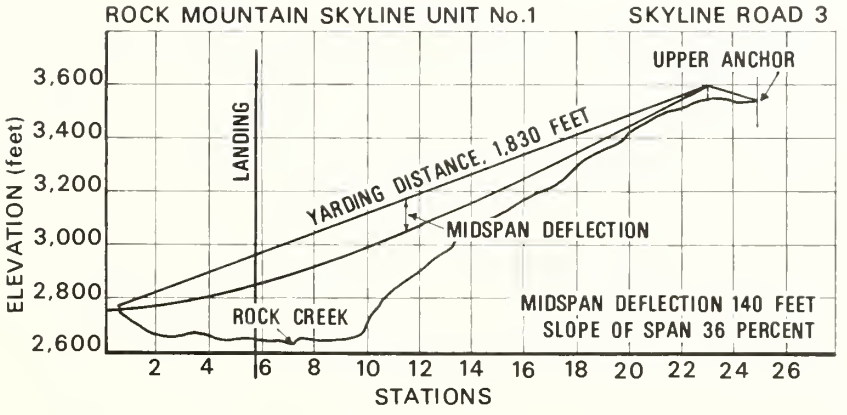

Figure 6.—Profile of skyline road 3, Rock Mountain skyline unit No. 1.

4.0 LOGGING COST ESTIMATE

Upon completion of cutting unit and profile designs, a final logging cost estimate should be made to confirm preliminary estimates and firmly establish economic feasibility. When this is done, normal procedures are then followed to implement the logging plan.

Binkley, Virgil W., and Lysons, Hilton H.
1968. Planning single-span skylines. U.S.D.A. Forest Serv. Res. Pap. PNW-66, 10 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

Single-span skylines require careful and thorough planning for successful operation. Criteria are presented for selecting areas suitable for skyline logging. A procedure is given that describes the steps that must be considered by the logging planner, from preliminary cutting unit layout to final location of the skyline roads.

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Headquarters for the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is in Portland, Oregon. The area of research encompasses Alaska, Washington, and Oregon, with some projects including California, the Western States, or the Nation. Project headquarters are at:

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Juneau, Alaska
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LITERATURE ON

TIMBER MEASUREMENT PROBLEMS IN THE DOUGLAS-FIR REGION

a bibliography compiled by

David Bruce

PACIFIC NORTHWEST
Forest and Range Experiment Station
U.S. Department of Agriculture · Forest Service
U.S.D.A. Forest Service Research Paper PNW-67
Portland, Oregon 1968

FOREWORD

This bibliography on timber measurements was prepared as part of an analysis of measurement problems in the Douglas-fir region of Oregon and Washington. It includes publications on the subject of tree or log measurement in this region with the exception of taper, volume, and yield tables and some standard forestry texts that made no specific reference to regional measurement problems. It also includes many publications that describe measurement systems or problems elsewhere in the United States and Canada and a few foreign publications that cover subjects not located in the American literature. A subject matter index is given on pages 27 and 28.

Appreciation is expressed to Mrs. Edith E. Bailey for listing and verifying most of the references.

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PRUNING OF PONDEROSA PINE..

EFFECT ON GROWTH

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JAMES W. BARRETT

PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
U.S.DEPARTMENT OF AGRICULTURE · PORTLAND, OREGON
U.S.D.A. FOREST SERVICE RESEARCH PAPER PNW-68 · 1968

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In Pacific Northwest ponderosa pine forests, investments in thinning have been favored over those for pruning. Now, there is evidence that adequately released crop trees are growing fast enough so that pruning for quality improvement may be a profitable investment. Also, with availability of a new self-propelled tree pruner (6) that can limb higher, faster, and possibly cheaper than conventional methods, interest has been stimulated in the profitable production of clear wood. However, with higher pruning in prospect, the amount of live crown removed becomes of concern. How much living crown can be removed without adversely affecting growth?

THE STUDY

Four 2-acre plots were established in 1941 in a 55-year-old stand of ponderosa pine on the Pringle Falls Experimental Forest in central Oregon where site index was 78 feet at 100 years (7). On each plot, 96 crop trees were selected and subdivided into four subplots of 24 trees of which six trees at random were assigned to each of four pruning treatments. Treatments consisted of (a) unpruned,[1/] (b) pruning of one-fourth, (c) one-half, and (d) three-fourths of the length of live crown.[2/] The amount of pruning necessary for each tree was determined by measuring live crown length to the nearest foot with a topographic abney level and tape and calculating the necessary pruning height to remove the appropriate amount of crown length. Dead branches were removed in all treatments. Trees were climbed to the desired length of removal and then pruned downward. Branches were left where they fell.

Trees chosen ranged from 6 to 18 inches in diameter, from 25 to 76 feet in height, and were representative

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[1/] Dead branches only were removed from trees referred to in the text as unpruned.

[2/] Live crown length, referred to in the text, is the distance along the main stem of the tree from the lowest living branch to the top of the tree.

of dominants or codominants. Averages for trees directly after study establishment were as follows:

Proportion of live crown removed	Diameter breast high (Inches)	Total tree height (Feet)	Height pruned (Feet)
0	10.10	46.5	13.3
1/4	10.42	48.2	22.6
1/2	10.60	47.5	30.6
3/4	10.59	47.0	38.5

Since live crown length and height to bottom branches of live crown before pruning varied markedly, there obviously was variation in crown length and pruned height between trees that received the same pruning treatment. Therefore, pruning one-fourth of the length of live crown from different trees could result in different volume of crown removed depending on original crown length.

Pruning dead limbs only resulted in clear bole lengths (table 1) ranging from 4 feet to 31 feet. Removal of lower one-fourth of the crown length gave clear bole lengths ranging from 12 to 37 feet; one-half, 17 to 47 feet; and three-fourths, 21 to 58 feet.

Height to live crown, total height, and diameter measurements and dominance classification were made at the time of study establishment and 5, 10, and 16 years later. Effects of pruning on growth during the first 5-year period were reported by Mowat (8) and during the 10 years subsequent to pruning by Dahms (1).

RESULTS

Diameter Growth

Pruning of live crown significantly

Table 1.--Number of ponderosa pine trees pruned in each clear bole length class, by proportion of crown length removed, 1941

Proportion of live-crown length removed	Clear bole length classes (feet)												Total
	4	8	12	16	20	24	28	32	36	40	44	48+	
	Number												
0	5	21	45	19	5	--	--	1	--	--	--	--	96
1/4	--	--	10	13	34	20	12	6	1	--	--	--	96
1/2	--	--	--	3	11	16	20	21	19	2	3	1	96
3/4	--	--	--	--	4	2	14	14	19	16	13	14	96

reduced subsequent diameter growth. Treatment averages show that the greater the proportion of crown length removed the less trees grew in diameter (fig. 1). During the first 5 years after pruning, trees with no live crown removed grew at the rate of 2.4 inches per decade (table 2). Removing one-fourth the live-crown length reduced this rate only about 6 percent; removing one-half and three-fourths reduced it by 25 and 63 percent, respectively.

As time passed and crowns increased in length (fig. 2), diameter growth rates tended to recover. For example, trees with only one-fourth of their live-crown length removed grew at the same rate as unpruned trees during the second (5 years) and third (6 years) periods. Even the most severely pruned trees showed substantial recovery by advancing from growth rates of only 37 percent of unpruned trees in the first period to 82 percent of unpruned trees during the third period.

There was a significant trend for larger trees to grow faster than smaller trees, except where three-fourths of the live-crown length was removed (fig. 3). For example, an average 8-inch tree with half its crown removed grew 2.4 inches in 16 years, but a 16-inch tree with the same treatment grew 3.3 inches. Increments on trees most heavily pruned were quite variable and failed to show any consistent relation to diameter at the time of pruning. By removal of the lower one-half of the crown length, diameter growth was reduced about 14 percent in 16 years throughout the range of tree diameters tested. In contrast, removal of lower one-fourth of the crown length only reduced diameter growth about 2.5 percent during the 16-year period.

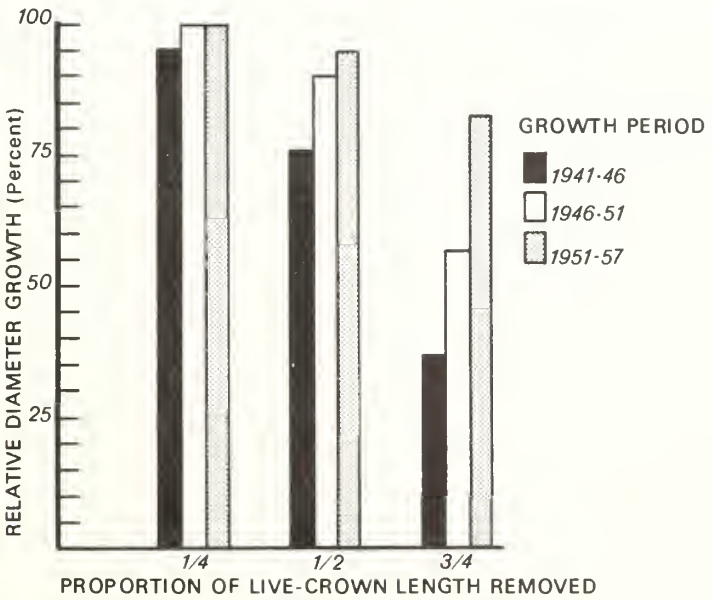

Figure 1.--Diameter growth of trees with live-crown length removed relative to those with only dead limbs removed.

Table 2.--Average annual diameter increment after pruning of ponderosa pine trees, by pruning treatment and growth periods

Proportion of live-crown length removed	1941-46	1946-51	1951-57	1941-57
	Inches			
0	0.239	0.179	0.173	0.195
1/4	.225	.177	.171	.190
1/2	.180	.159	.163	.167
3/4	.088	.102	.142	.112

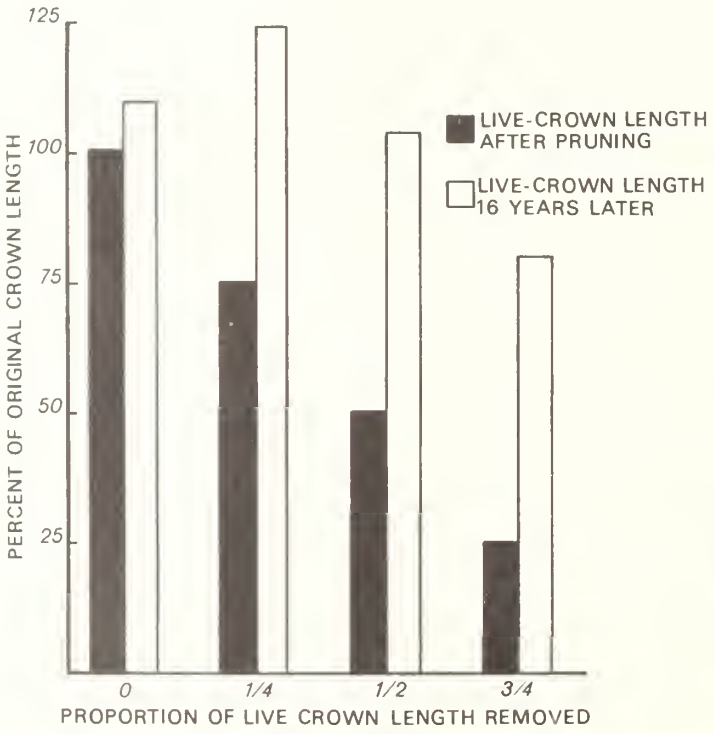

Figure 2.--Live-crown length directly after pruning and 16 years later.

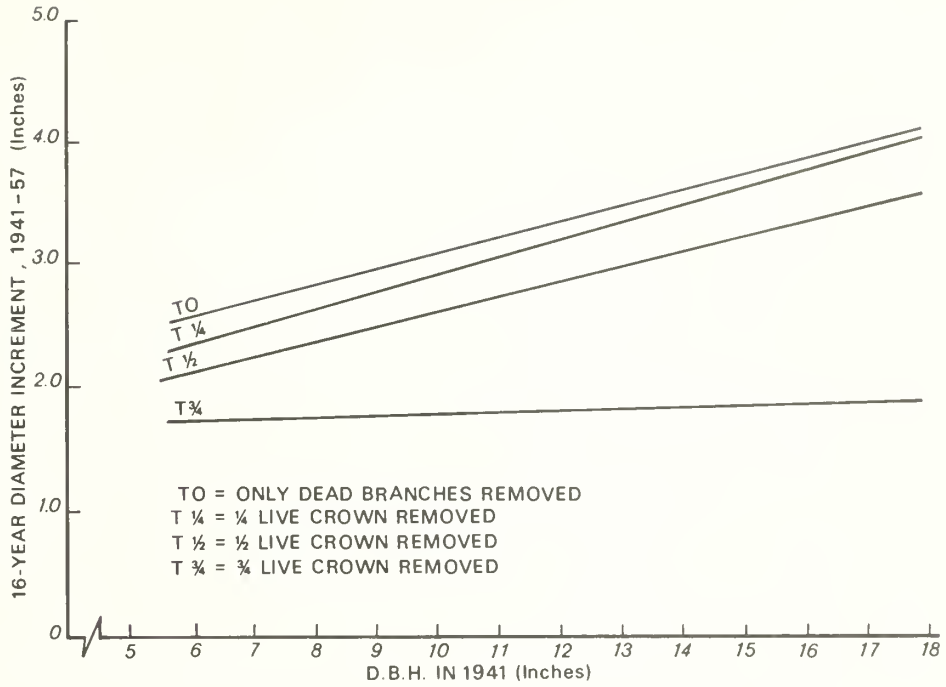

Figure 3.--Relation of 16-year diameter growth to diameter in 1941.

Initial crown length, as well as the proportion removed, affected diameter growth. Among trees within each treatment, diameter growth during the 16 years was significantly correlated with length of live crown before pruning (fig. 4). Thus, trees having a large portion of their total height in crown were less affected by pruning than trees with only a small portion of their height in live crown. Also, there is some evidence shown in the response surface in figure 4 to indicate the removal of lower, shaded branches on large-crowned trees will increase increment.

Height Growth

Height growth was reduced in proportion to severity of treatment, although differences were not great (table 3). During the 16 years, trees that had no live crown removed grew 1.24 feet per year compared with 1.12 feet for the most severly pruned trees. Therefore, the total height of pruned trees differed little from untreated trees in the stand. To illustrate, the average height difference between none and three-fourths crown-length removal amounted to only 2 feet during the 16 years.

Despite these small effects of treatment on height growth, loss of dominance was evident. The percent of trees losing at least one step in dominance during the 16 years follows:

Proportion of live-crown length removed:	Trees with lowered dominance (Percent)
None	10
One-fourth	19
One-half	19
Three-fourths	29

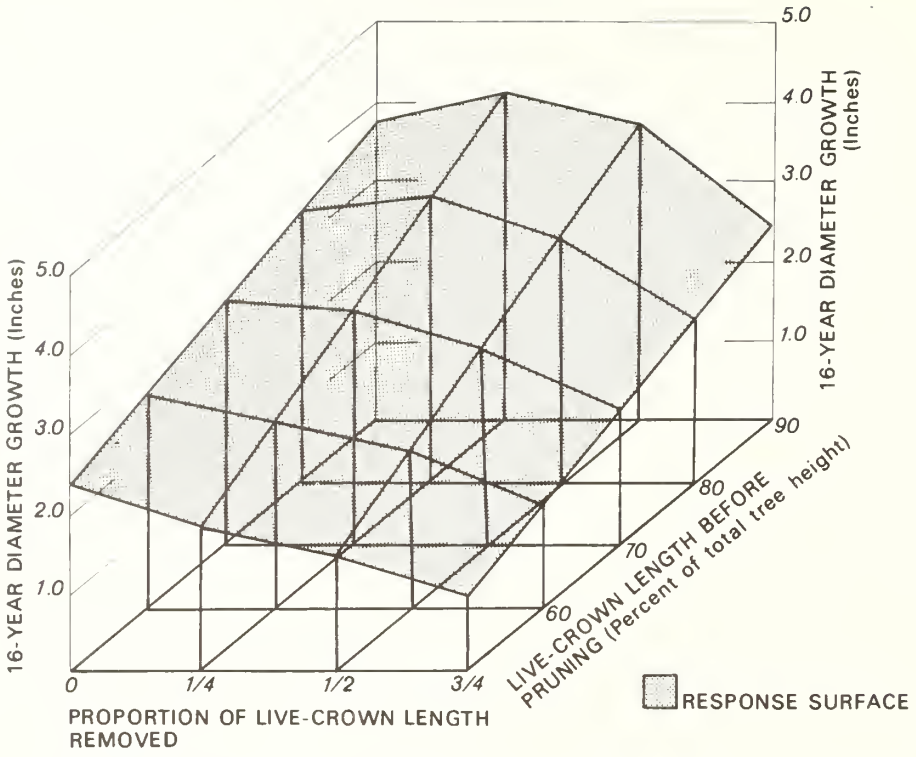

Figure 4.--Diameter growth when various lengths of ponderosa pine crowns are removed.

Table 3.--Average annual height growth after pruning of ponderosa pine trees by pruning treatment and growth periods

Proportion of live-crown length removed	1941-46[1/]		1946-51[1/]		1951-57		1941-57	
	Feet	Percent[2/]	Feet	Percent	Feet	Percent	Feet	Percent
0	1.172	100	1.336	100	1.228	100	1.244	100
1/4	1.101	94	1.348	101	1.245	101	1.233	99
1/2	1.101	94	1.221	91	1.217	99	1.182	95
3/4	1.061	91	1.205	90	1.097	89	1.119	90

[1/] Averages differ slightly from those published by Dahms (1) because trees whose tops were damaged during the last period were dropped from height analyses.

[2/] Percent is of height growth for unpruned trees.

A few trees in all treatments gained in dominance, but most trees lost.

Mortality

Pruning intensity had little effec on mortality. Even trees that had only a few green branches left after pruning remained vigorous. Although half the trees were deliberately pruned at the peak of insect activity, just one died during the first 5 years. Only three trees died during the entire 16 years of observation--one with only dead limbs removed and two with three-fourths of their lower live-crown length removed.

RECOMMENDATIONS AND DISCUSSION

On the basis of 10 years' data, Dahms (1) concluded that "... not more than one-third of the length of the live crown should be removed and that the crown in no event be reduced to less than one-third of the total height of the tree." After 16 years, this same generalization is sound but, with additional data available, separate recommendations can now be made for pruning trees having different initial lengths of live crown.

Existing live-crown length has an important bearing on the percent of crown length that should be pruned from a tree. Full-crowned trees can tolerate more pruning than short-crowned trees. There is, therefore, a variable limit to the number of live branches that can be removed without reducing diameter growth an unacceptable amount.

Obviously, the tolerable amount of growth reduction must be selected by the forest manager after due consideration of management objectives. Table 4 presents growth reductions that can be expected with different lengths of live-crown removal. For example, a tree with 60 percent of its total height in crown could have 20 percent of its lower crown length removed and suffer only 11-percent reduction in diameter growth over a 16-year period. In contrast, a tree with 80 percent of its height in crown could have 30 percent of its lower crown length removed and still maintain its initial diameter-growth rate. If the forester can tolerate very little loss in diameter growth, he should use crown removal and total crown combinations, represented by low percent diameter-growth reductions in the body of table 4.

Removal of 25 percent of the lower live-crown length on full-crowned trees appears to increase subsequent diameter growth (fig. 4). Others have observed this trend in either or both diameter and height growth for pruned Douglas-fir (9), western white pine (5), and ponderosa pine in California (10, p. 3).

One might speculate whether crown recovery (fig. 2) would be the same in a thinned stand of widely spaced trees. Lower branches on an unpruned tree probably would not die as rapidly in a thinned stand as in an unthinned stand. Therefore, in a thinned stand it is unlikely that live crown on trees pruned one-fourth and one-half their lower crown length would equal the crown length for unpruned trees within 16 years.

Data in table 4 and figure 4 indicate that 50 percent of the lower crown

Table 4.--Estimated reductions in diameter growth of ponderosa pine trees caused by removing different proportions of live crown, 16 years after pruning

Portion of total tree height in live crown (percent)	Percent of crown removal								
	10	20	25	30	40	50	60	70	75
	Percent[1/]								
50	10	21	27	28	32	37	46	54	59
60	6	11	13	16	22	25	38	49	50
70	1	2	3	7	14	16	30	40	44
80	0	0	0	0	5	8	23	33	39
90	0	0	0	0	0	1	14	28	34

[1/] Estimated by graphic interpolation of figure 4.

length can be removed on full-crowned (80 to 90 percent of height) trees without causing much reduction in diameter growth. Somewhat the same conclusion was drawn by Hallin (3), and later confirmed by Gordon (2), on a similar study in California, where they recommended removal of up to one-half of the green crown on open-grown trees if four-tenths of the total height remained in green crown. They found that trees with 50 percent of the live crown removed suffered shock initially, but after 5 years "...their growth almost paralleled that for unpruned trees," which grew 3 inches in diameter per decade. Removal of the lower one-fourth of the crown length had no effect on diameter growth, but removal of three-fourths of the crown length reduced growth drastically and 52 percent of trees pruned that much died from insect attack.

Heidman (4), working in the Southwest, found that 40 percent of the live crown can be removed without significantly affecting diameter growth if at least 31 percent of total tree height is left in live crown. He also found crown length to be an important factor in specifying treatment. He suggested that the Southwestern study would have been more meaningful if trees had been pruned to leave specified percentages of tree height in live crown.

Since results from this study and several other ponderosa pine pruning studies essentially agree, the recommendations presented here should be used to sharpen up or modify existing ponderosa pine pruning practices.

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The ratio of existing crown length to total height has an important bearing on the proportion of crown length that should be pruned from ponderosa pine. Therefore, there is a variable limit to proportion of crown length that can be removed and still maintain acceptable growth rates. A table is presented that shows diameter growth reduction that can be expected from removing different proportions of live crown length.

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Elytroderma Disease of Ponderosa Pine in the Pacific Northwest

T. W. Childs

U. S. D. A. Forest Service Research Paper PNW-60
1963

Summary

The needle cast of *Pinus ponderosa* caused by *Elytroderma deformans* is a native disease that intermittently causes severe local damage. The fungus is perennial within the host, where it spreads vegetatively from one twig or branch to another. Even in its vegetative stage the fungus appears unusually sensitive to climatic stresses.

Foliage on infected twigs dies early in its second year, and the twigs usually die within a few years. Growth rates are reduced in approximate proportion to extent of crown damage. Uncrowded saplings and poles with healthy leaders can recover eventually from fairly severe infection if they are not attacked by other parasites while weakened. In mature stands, crown damage from extensive killing of twigs and branches is permanent, moderately infected trees become and remain more susceptible to root disease and beetle attack, and heavily infected trees are often killed directly by defoliation.

Despite its alarming appearance in outbreak centers, the disease is just another of the many normal hazards to which forests are subject. It does not threaten to exterminate ponderosa pine as a commercial species even on local areas, and usual good management practices should go far towards reducing its future inroads.

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Introduction

The disease caused by *Elytroderma deformans* (Weir) Darker[1] has been conspicuous during recent years in many ponderosa pine (*Pinus ponderosa* Laws.) stands from southern British Columbia to northeastern California and western Montana. Although less destructive than its alarming appearance often suggests, it has reduced growth rates on more than 100,000 acres in Oregon and Washington and has killed many trees on a few areas of severe infestation, sometimes more than 1,000 acres in extent. Heaviest damage has occurred in central and northeastern Oregon.

This paper is concerned with the disease only on ponderosa pine and principally with its behavior and effects east of the Cascade Range in Oregon and Washington. It is generally less damaging in other regions and to other hosts.

[1] *Originally described by Weir (1916) as* Hypoderma deformans. *It is commonly called needle blight or needle cast, but "Elytroderma disease" seems preferable since it also invades and damages twigs, branches, and young trunks.*

Occurrence and Persistence of Outbreaks

Weir's (1916[2]) observations in 1913-15 were evidently made during the waning stages of an extensive outbreak that had started many years before. Damage from this or possibly a later and less extensive outbreak continued for several years in parts of southern Idaho. In Oregon and Washington during the 1920's and 1930's, large brooms (presumably relics of the outbreak described by Weir) were fairly common in some localities, but no damage was observed even where Weir had recorded the disease as destructive.

The current outbreak first attracted attention in 1945 in central Oregon. During the next few years, the disease was found to be occasional to common in stands of all ages throughout the region. Evidence to be presented later indicates that a heavy wave of infection occurred in the late 1930's or very early 1940's. Some subsequent infection by spores has occurred from time to time.

Severe damage has been confined to relatively small areas within a rather narrow altitudinal zone centered at about 5,000 feet in central Oregon (Hunt and Childs 1957) and 3,500 feet in northern Washington. By 1950, nevertheless, salvage of more than 100 million board feet of sawtimber became necessary on the Ochoco National Forest alone, and infection of pole and sapling stands was causing serious concern. The disease is less conspicuous today (1967), but it is still common, killing or stunting trees on areas where it was causing damage 20 years ago.

Almost simultaneous appearance of heavy infection in localities hundreds of miles apart indicates regionwide occurrence of some combination of weather conditions especially favorable for infection, but weather summaries have provided no clue to the origin of the outbreak. Contrary to Weir's (1916) experience, recent investigators have usually found it difficult to germinate spores (Lightle 1954) and infect trees experimentally (Roth 1959, Waters 1957); consequently, little progress has been made in studies of epidemiology of the disease.[3]

Persistence of outbreaks, however, is easily explained. Elytroderma invades twigs and buds as well as needles, survives perennially in the former, and spreads vegetatively into needle primordia (Sikorowski and Roth 1962, Waters 1962, Weir 1916). Thus, once a damaging wave of infection has occurred, the fungus is not dependent on annually recurring periods of weather favorable for spore germination and host invasion in order to continue causing damage for many years.

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[2] *Names and dates in parentheses refer to Literature Cited, p. 38.*

[3] *Gordon and Laurent report successful inoculations of needles not more than 3 weeks old (personal communication). They suggest that infection waves may occur when ascocarp development is retarded by unfavorable weather so that infected needles remain on the tree and produce ascospores in the spring.*

Description of the Disease

The most prominent feature of Elytroderma disease is the red-brown "flags" which appear in spring. On flagged twigs, many of the B needles[4] are reddened, usually throughout all except their basal one-fourth or one-half inch. Ordinarily, either all or none of the needles in a bundle are affected. Reddened bundles tend to be grouped rather than randomly intermingled with green ones, and to be most numerous toward the distal end of the twig segment. A needles are not reddened, although sometimes faded, by October. Older than B needles usually are not reddened (exceptions will be discussed later), but twigs flagged in the previous year have lost many of these older needles.

Several other diseases cause somewhat similar discoloration, but in spring and early summer an experienced observer can usually identify Elytroderma flags, even in tops of tall trees, by their color.[5] Reddened needles gradually fade and become partly obscured by new foliage; by late summer they are indistinguishable, at distances of more than a few feet, from old needles fading in the course of normal fall defoliation. Most of the faded needles drop from the tree during the winter.

In spring the reddened needles produce small translucent beads or fine tendrils of pycnidiospores, which persist until dissolved by rain or broken off. Dark lines appear on the outer (rounded) surfaces of the needles in May or June, become plainly visible as the season progresses, and by late summer develop into conspicuous black fruiting bodies (fig. 1, A and B) in which ascospores are produced.[6]

Elytroderma fruiting is sometimes sparse throughout much of the region. Distal parts of discolored needles then usually bear small, crowded, black fruiting bodies of another fungus possibly competitive with Elytroderma or even parasitic upon it.

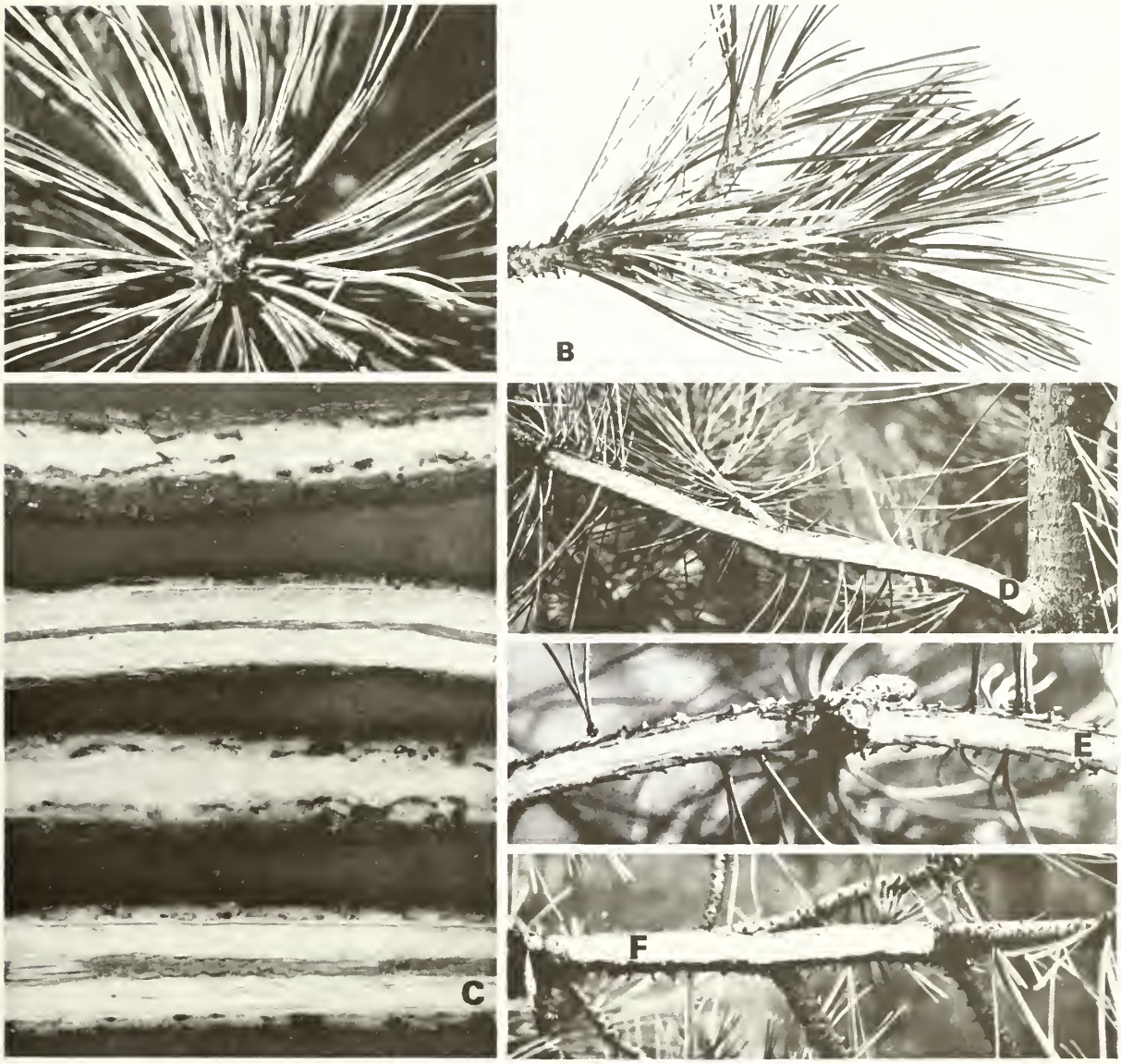
Lesions characteristic of the disease (Lightle 1954) occur in the inner bark of infected branches and are plainly visible in branch segments from 2 to 10 or 12 years old (fig. 1, C, E, F, and G). Even in old branches that have just flagged for the first time, lesions are often abundant throughout all except the youngest segments and, at least in saplings, in adjacent parts of the trunk and in bases of unflagged branches in neighboring whorls. Slender stems invaded by Elytroderma soon become noticeably deformed.

Twigs once flagged usually flag again each spring and soon curve upward (fig. 2A). Vigorous infected branches on thrifty trees often develop into dense, irregular or usually roughly globose witches-brooms (fig. 2, B to D) which survive and

[4] *A needles are those produced during the current calendar year; B needles, during the preceding year.*

[5] *Winter-injured foliage, for example, is often mistaken for Elytroderma flagging, but is a paler red. Other differential characteristics of winter injury are its usually greater abundance in tops than in bottoms of crowns, usual restriction to the distal half of the needles, gradual instead of abrupt transition between killed and living tissues, and, of course, the absence of Elytroderma fruiting bodies. Unlike Elytroderma, winter injury and most other foliage diseases are seldom conspicuous in successive years.*

[6] *Ascospores cause new infections. Pycnidiospores are probably functionless. Darker (1932) describes and illustrates both kinds of spores and the fruiting bodies that produce them.*



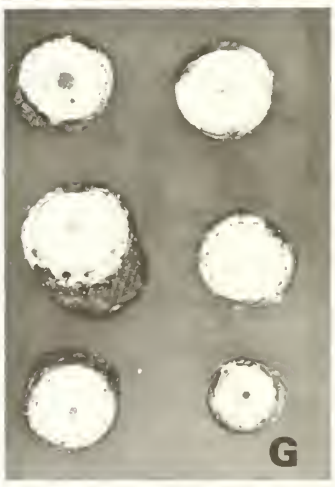


Figure 1. — A, Ascospore fruiting bodies of Elytroderma in late June (unusually conspicuous for so early in the year); B, ascospore fruiting bodies (dark lines) in late October (black dots are other fungi saprophytic on killed needles); C, tangential and radial sections of small branches showing necrotic lesions in inner bark; D, tangential section of healthy branch; E and F, tangential sections showing bark lesions in branch segments 3 to 4 and 9 to 10 years old, respectively; G, cross sections showing lesions in inner bark of young branches (section at upper right is from a healthy branch).

grow indefinitely. Flagged twigs on unbroomed branches gradually decline in vigor and seldom survive for more than a few years.

Variation from tree to tree in severity of infection undoubtedly is due partly to differences in susceptibility, but much of it obviously is associated with environmental differences. Infection is usually heaviest on pole and large-sapling understories, in the interiors of crowded groups of trees, and on lower branches and north to northwest sides of trees. Hunt and Childs (1957) found infection most abundant in stands of moderate density, at edges of meadows,[7] in wide draws, and on lower gentle slopes. These habitat preferences appear largely attributable to moisture requirements for spore germination, but some of them, together with other evidence, suggest that Elytroderma is relatively intolerant of high temperatures.

Small saplings probably were badly damaged in some localities during early years of the current outbreak but now are generally uninfected or only lightly infected. Trees that originated after about 1940 were not exposed to the main wave of infection, while many of the slightly older trees escaped it because of the small target they then exposed to infection. Despite the great numbers of ascospores since produced, infection is still not common on trees less than about 30 years old.[8]

In most localities, infection was never very damaging in any tree-size class, even though it was often conspicuous. Here the only signs of the disease have been the flags, still common on some trees, and in recent years, occasional to common brooming. Crowns of some thrifty young trees now consist of an outer layer of normal density formed by continued growth of uninfected branches, and a shorter, narrower, and denser inner part formed by broomed branches (fig. 2C).

Where infection was moderately heavy, most twigs in lower quarters or thirds of the crowns and many twigs higher in the crowns were flagged during early stages of the outbreak. Direct killing was rare here, but mortality increased from bark beetles[9] and apparently also from root diseases, often necessitating salvage logging. The unbroomed old flags are now dead, leaving crowns thin and ragged (fig. 2, D to G), often short, and spotted with newer flags.

Where infection was heaviest, entire lower crowns and many of the upper-crown twigs were soon killed. On some trees, more than nine-tenths of the twigs were either killed or flagged within a few years. Mortality became so common that mature stands were hastily logged except on small areas reserved for research. Many trees on reserved areas have since died and most survivors are in poor condition. In pole stands, survivors are partly compensating for destruction of lower crowns by adding new growth at the top, and often appear to be recovering.

In general, damage was considerably slower than at first expected, but it continued far longer and results were much the same even though the damage consisted less of rapid, direct killing than of progressive attrition of crowns and creation of high-risk trees.

[7] *Probably because of the effects of these openings on temperature and humidity (Selleck and Schuppert 1957). Even in very dry periods, fog often forms at night over large "prairies" and then drifts into the neighboring forest (personal communication from R. W. Ellstrom).*

[8] *In 1949 and 1950, the disease was found on "trees of all sizes, from seedlings 6 inches high to mature trees. The youngest infected tree found . . . was determined to be 11 years old; only 1 such plant was found. Infected trees 12 years old were fairly common, but infection was more abundant in trees 14 years old and older" (Lightle 1954). In 1965 and 1967, two brief searches where the disease was common on large trees disclosed several old flags on trees 9 to 12 years old.*

[9] *According to personal communications from foresters in outbreak localities,* Dendroctonus brevicomis *populations increased in moderately infected stands more than in severely infected ones – presumably because saturated sapwood and sour smell of heavily defoliated trees make them unattractive to beetles.*

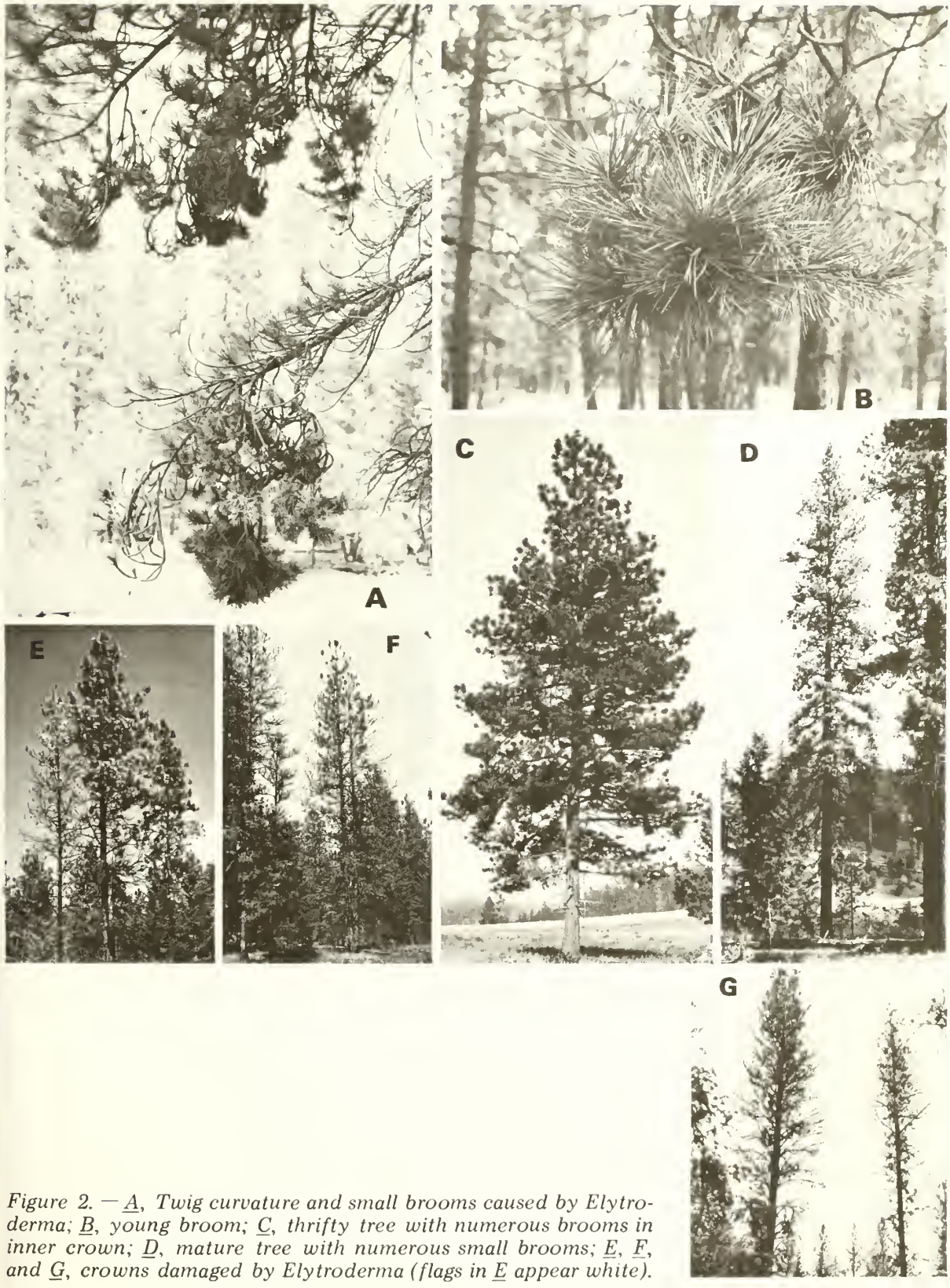


Figure 2. — A, Twig curvature and small brooms caused by Elytroderma; B, young broom; C, thrifty tree with numerous brooms in inner crown; D, mature tree with numerous small brooms; E, F, and G, crowns damaged by Elytroderma (flags in E appear white).

Studies and Plots

Early investigations of the current outbreak were limited to general observations since it was expected to subside within a year or so, as do most foliage disease outbreaks. Plot records consequently do not cover early stages of the outbreak. Studies were started in 1949 to determine the effects of different intensities of infection on mature stands. Damage plots were established in young-mature and old-growth stands where Elytroderma had caused little or no mortality but where severe damage was thought to be imminent. It soon became evident that data were also needed from smaller trees to help explain the behavior of the disease as well as to guide management of young stands.

This report is based principally on plots listed in table 1. Additional information was obtained from surveys, plots maintained only for brief periods, and tagged saplings used in fungicide tests. Data were also provided from five damage plots in mature stands in south-central Idaho; records indicated that effects of the disease there had been much the same as on the Oregon and Washington plots (see appendix).

Disease Behavior on Saplings

On the disease behavior plots, selected saplings more than 20 years old (and a few younger ones at Camas Creek) were examined annually in spring or early summer. Most of these trees had healthy leaders, were no more than lightly infected in the rest of the crown, and were no more than moderately crowded. Overstory density ranged from practically none at Camas Creek to light at John Day and Deer Creek.

Each branch with one or more flagged twigs was tagged, its position on the tree noted, its terminal (primary) twig recorded as flagged or healthy, and its flagged and total year-old and older lateral twigs tallied. Twigs were classed as "recovered" when they failed to flag after having formerly been flagged. Dead laterals were clipped to permit recognition of "recovered"[10] ones in subsequent examinations. General notes were taken on flag color, abundance and stages of development of Elytroderma fruiting bodies, and occurrence of fruiting bodies of other fungi on needles of flags. At Camas Creek, records of individual twigs were kept by means of branch diagrams. On the other two plots, regular data were supplemented by explanatory notes whenever changes in condition could be determined

[10] *Quotation marks are retained because subsequent behavior of many "recovered" twigs, branches, and trees indicated that they were still infected even though symptoms were not visible.*

TABLE 1. – LOCATIONS AND DESCRIPTIONS OF ELYTRODERMA STUDY PLOTS

Study and plot	Period of study	National Forest	Ranger District	Slope	Aspect	Elevation	Area	Number of trees	Average tree size[1]	
									D.b.h.	Height
						Feet	*Acres*		*Inches*	*Feet*
Disease behavior on saplings:										
1. John Day	1953-65	Malheur	Blue Mountain	Moderate	S.	4,900	([2])	70	--	7.6
2. Deer Creek	1954-65	Malheur	Bear Valley	Moderate	NW.	5,300	([2])	22	--	6.8
3. Camas Creek	1957-65	Umatilla	Ukiah	Moderate	SE.	4,700	([2])	67	--	7.5
Damage to poles:										
4. Dead Injun	1955-64	Malheur	Bear Valley	Gentle	SW.	5,200	10	281	7.5	--
5. Opal Flat	1955-65	Umatilla	Heppner	Level	--	4,400	7	224	9.5	--
6. Austin	1955-65	Malheur	Blue Mountain	Gentle	SW.	4,600	2	209	6.9	--
7. Chewiliken[3]	1956-65	--	--	Gentle	SW.	3,400	3	132	8.7	--
Damage to young-mature trees:										
8. John Day	1949-66	Malheur	Blue Mountain	Moderate	S.	4,900	5	110	17.5	--
9. Bannon	1956-65	Okanogan	Tonasket	Moderate	E.	3,500	4	115	13.5	--
Damage to old growth:										
10. Grays Prairie[4]	1949-65	Ochoco	Big Summit	Gentle	N.	5,200	28	335	27.2	--
11. Wildwood[4]	1949-65	Ochoco	Big Summit	Moderate	S.	5,000	6	177	26.7	--
12. Deer Creek	1951-65	Malheur	Bear Valley	Moderate	NW.	5,300	6	103	24.7	--
13. Belshaw	1951-66	Malheur	Long Creek	Moderate	SW.	5,200	5	159	23.8	--

[1] *At time of plot establishment.*

[2] *Indefinite.*

[3] *The Biles-Coleman Co. furnished assistance as well as study area.*

[4] *Strips 2 chains wide. All other plots were only about twice as long as wide.*

for individual twigs. Approximate numbers of uninfected branches and twigs upon them were computed from samples, as were tree height increments. A few additional data were obtained after the principal study on these plots had been terminated.

Numbers and conditions of trees, branches, and twigs (except branches and twigs in the few infected leader systems) are given in tables 2, 3, and 4 for each year of the study on the disease behavior plots. Here and elsewhere, uninfected classes include only units never recorded as flagged (some of these no doubt were invisibly infected). "Recovered" trees and branches are those once flagged but whose flagged twigs had all "recovered" or died. "Recovered" units are classed as infected.

Changes in amount of infection (except changes from additions to the basis in 1954, 1955, and 1957) were caused by appearance of new flags, death or "recovery" of flagged twigs, and death or relapse of "recovered" twigs:

Change from year before	Average annual change during study	
	Terminals	Laterals
	(Percent)	
New laterals[1] flagged on previously infected branches:		
On branches with infected terminals	--	78.9
On branches without infected terminals	--	11.5
Old twigs[1] flagged for first time:		
On branches previously infected	7.4	5.5
On branches not previously infected	.3	.2
Flagged twigs died	22.3	22.6
Flagged twigs "recovered"	6.9	5.0
"Recovered" twigs died	17.6	21.0
"Recovered" twigs relapsed	14.1	23.5
Uninfected twigs died on infected branches	8.0	7.7

[1] *New laterals are those just old enough to flag – that is, in their second growing season; old twigs are terminals and laterals in at least their third growing season.*

The much more frequent flagging of new laterals associated with infected terminals, as compared with those associated with uninfected terminals, substantiates Waters' (1958) and Sikorowski and Roth's (1962) conclusion that shoot primordia become infected vegetatively by growth of the fungus in the terminal bud. Other evidence indicates that the fungus also spreads vegetatively from twig to twig along branches, as suggested by Roth (1959), and even from branch to branch along trunks. Such spread requires consideration at some length.

Evidence of vegetative spread. — Of the 1,085 new flags recorded during the study, more than half occurred on branches previously flagged, even though such branches constituted only 11 percent of the branches on infected trees (7 percent of branches on total trees) and were often intermingled with branches, on the same or other trees, that never became flagged. On branches flagging for the first time, 59 percent of the flags appeared in groups of two or more per branch and

TABLE 2. – NUMBER AND CONDITION OF TREES ON DISEASE BEHAVIOR PLOTS, BY YEAR OF EXAMINATION

Condition of trees	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
	Number of Trees												
Flagged — added to basis	36	12	17	0	21	0	0	0	0	0	0	0	0
Not flagged — added to basis	--	10	17	0	46	0	0	0	0	0	0	0	0
Flagged year before — still flagged	--	36	46	56	52	71	82	67	31	30	48	47	46
Flagged for first time	--	--	1	1	2	8	1	2	0	0	0	0	0
Relapsed	--	--	--	0	1	4	0	0	0	20	5	2	3
Flagged year before — "recovered"	--	0	2	8	5	5	1	16	38	1	2	6	3
"Recovered" trees died	--	--	--	0	0	0	0	0	2	0	0	0	0
Total flagged	36	48	64	57	76	83	83	69	31	50	53	49	49
Total "recovered"	0	0	2	10	14	15	16	32	68	49	46	50	50
Total uninfected	0	10	26	25	69	61	60	58	58	58	58	58	58

TABLE 3. — NUMBER AND CONDITION OF BRANCHES ON DISEASE BEHAVIOR PLOTS, BY YEAR OF EXAMINATION

Condition of branches	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
	Number of branches												
Infected branches:													
On trees added to basis	79	22	31	0	60	0	0	0	0	0	0	0	0
Flagged year before —													
still flagged	--	75	104	153	142	207	226	162	60	50	111	111	110
Flagged for first time on:													
Tree already flagged	--	16	46	14	36	34	36	4	2	27	13	10	13
"Recovered" tree	--	--	--	0	0	6	0	0	0	13	5	3	3
Previously uninfected tree	--	--	1	1	2	8	3	3	0	0	0	0	0
Relapsed	--	--	0	0	1	5	2	1	1	40	11	3	2
Flagged year before — "recovered"	--	1	2	13	8	11	15	54	71	3	10	14	7
Flagged year before — died	--	3	7	16	18	23	19	51	39	10	9	15	10
"Recovered" branches died	--	--	0	0	2	1	3	4	15	22	5	1	8
Total flagged branches	79	113	182	168	241	260	267	170	63	130	140	127	128
Total "recovered" branches	--	1	3	16	21	26	36	85	140	81	75	85	82
Uninfected branches:[1]													
On flagged trees	425	636	843	807	1,348	1,609	1,658	1,555	811	1,231	1,300	1,264	1,278
On "recovered" trees	--	--	27	146	212	232	254	555	1,403	1,078	1,130	1,238	1,317
On uninfected trees	--	180	370	376	1,647	1,503	1,568	1,575	1,640	1,727	1,796	1,872	1,941

[1] *Estimated from samples.*

TABLE 4. – NUMBER AND CONDITION OF TWIGS ON DISEASE BEHAVIOR PLOTS, BY YEAR OF EXAMINATION

Condition of twigs	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965
	Number of twigs												
Infected twigs:													
On trees added to basis	136	62	61	0	168	0	0	0	0	0	0	0	0
Flagged year before--													
still flagged	--	130	231	314	311	519	509	353	115	109	248	252	257
Flagged for first time on:													
Branch already flagged	--	42	29	45	68	109	77	41	18	42	32	35	39
"Recovered" branch	--	--	0	0	0	4	3	1	0	24	3	4	2
Branch previously uninfected	--	34	82	22	61	65	56	8	4	63	27	23	22
Relapsed	--	--	--	0	2	7	3	0	3	71	12	5	2
Flagged year before—"recovered"	--	0	5	10	6	14	28	50	113	1	6	11	3
Flagged year before — died	--	6	32	79	64	77	167	245	175	30	55	59	59
"Recovered" twigs died	--	--	--	1	2	0	4	15	27	29	9	4	10
Total flagged twigs	136	268	403	381	610	704	648	403	140	309	322	319	322
Total "recovered" twigs	--	0	5	14	16	23	44	79	162	63	48	50	41
Uninfected twigs:[1]													
On flagged branches	204	249	402	386	594	653	664	467	203	446	470	421	411
On "recovered" branches	--	2	7	37	47	63	87	217	407	269	254	286	259
On uninfected branches:[2]													
On infected trees	2,052	3,210	4,330	4,741	9,396	11,103	11,535	12,725	13,370	13,965	14,704	15,130	15,705
On uninfected trees	--	909	1,841	1,870	9,920	9,065	9,460	9,499	9,904	10,445	10,868	11,320	11,747

[1] *1 year old or older (twigs in their first growing season are not flagged by Elytroderma).*

[2] *Estimated from samples.*

30 percent in groups of three or more, even though less than 1 percent of the previously uninfected branches became flagged in an average year. On branches previously flagged, new flags also tended to appear in groups, usually adjacent to older flags.

During the 8 to 12 years they were under observation, more than 22 percent of previously uninfected branches became flagged on trees bearing old flags and nearly 5 percent on "recovered" trees, but only 1.4 percent on previously uninfected trees. Like newly flagged twigs, branches flagged for the first time tended to occur near previous flagging.

On 24 of the 98 trees flagged before 1959, visible infection remained confined to one branch (on 11 of these trees, to one twig) during the remainder of the study. On other trees it often skipped some twigs or branches more or less permanently. Nevertheless, nonrandomness of flagging was far too consistent to be attributed entirely or even largely to differences in microenvironments and tree susceptibility. Two examples of close association of new flagging of twigs and branches with older flagging are shown in figure 3.

In A to D of figure 4, bark lesions caused by Elytroderma are shown[11] in trunks and branches above the highest flag. In D and F of this figure, 3-year-old needles on one branch and 2-year-old needles on three branches and a leader are flagged where all younger needles have remained green. On twigs flagged more than once it is very rare for even a single 2-year-old or older needle to show signs of Elytroderma infection. On new flags, however, flagging of 2-year-old needles, followed by typical Elytroderma fruiting, is common; such flagging clearly indicates that the needles have been invaded by growth of the fungus from the base toward the tip of the twig instead of from meristem into primordia in the bud.

Extent and importance of vegetative spread. — Rate of vegetative spread could be estimated only in general terms, partly because it seemed to be strongly affected by bark age and condition, and partly because of evident variations in length of period between invasion of foliated twig segments and appearance of the flags.[12] In most trees on the disease behavior plots, spread rate appeared to be only a few inches — perhaps 4 or 5 — per year in the lower and central parts of the crowns, but two or three times as fast in vigorous tops and branches.

Distal spread is more common, or at least more rapid and extensive, than proximal spread. Branch infections in tops of young trees often spread to leaders (for example, as in figure 4F), making trees worthless for timber production. Of the 10 saplings whose leaders became flagged during the study, nine had branches previously flagged within 3 feet of the leader.

Thrifty saplings infected only in the lower crowns grow faster than the infections advance upward, and sooner or later are probably freed of visible infection through suppression of lower branches and action of other factors adverse to the disease. Long-term effects of stem deformation and phloem injury on quality and volume increment are unknown.

In larger trees, vegetative spread from branch to branch is probably not common, since initial infection by spores occurs at a greater average distance from the trunks than it does in saplings, and since growth of the fungus along branches is probably slower. However, larger trees have more twigs per branch, and twig-

[11] *Lesions are shown in figure 4 only where they could be attributed with reasonable certainty to Elytroderma. They are often hard to identify in old or long-infected bark. Diagrams* E *and* F *were drawn from photographs in which some of the details were obscure.*

[12] *For example, a badly stunted tree at Deer Creek remained for at least 11 years with only the two lowest branches flagged. Then, in 1966, its leader (about 2½ feet from the basal flags) and nine of its 10 intervening branches flagged simultaneously.*

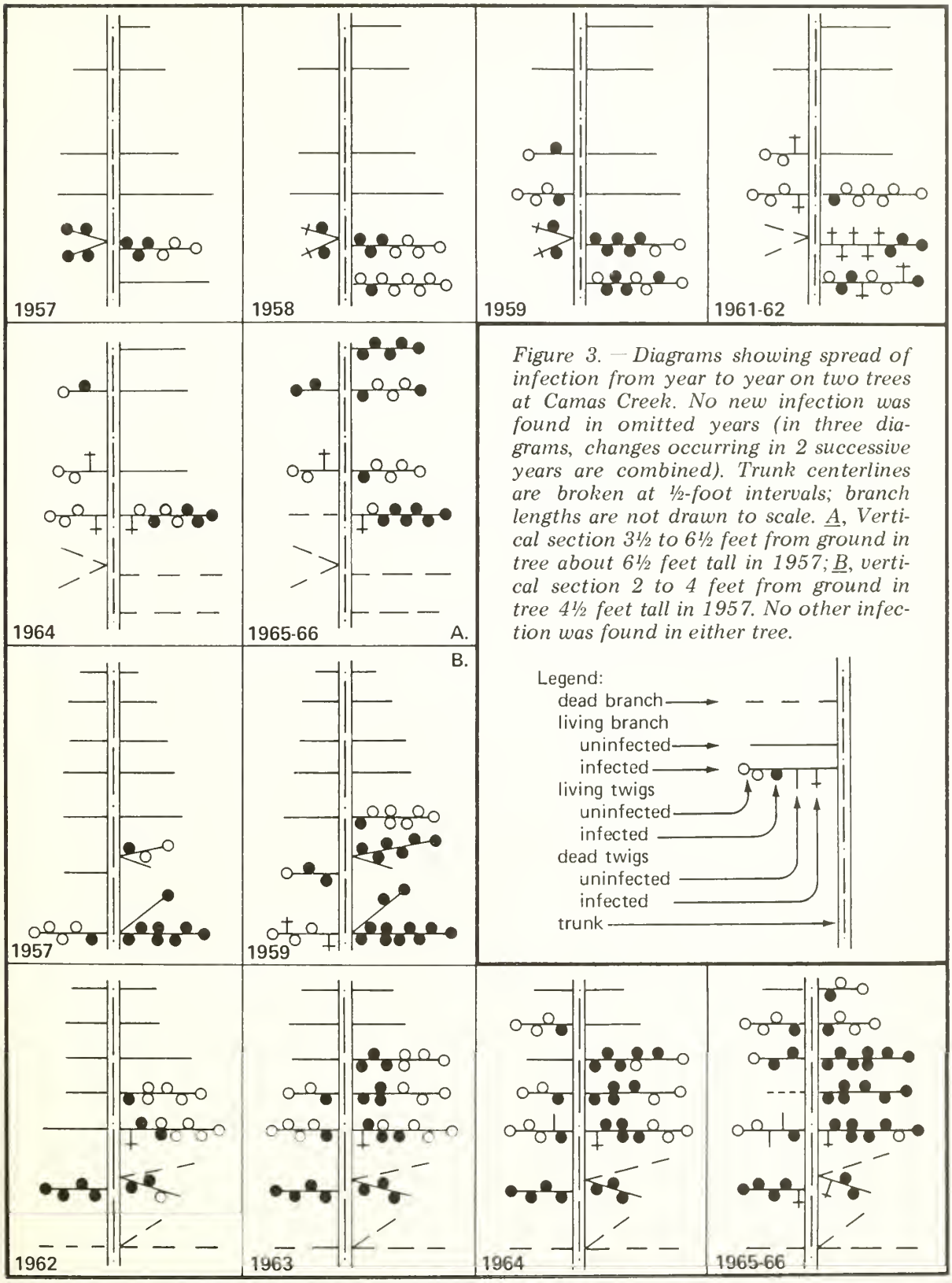


Figure 3. — Diagrams showing spread of infection from year to year on two trees at Camas Creek. No new infection was found in omitted years (in three diagrams, changes occurring in 2 successive years are combined). Trunk centerlines are broken at ½-foot intervals; branch lengths are not drawn to scale. A, Vertical section 3½ to 6½ feet from ground in tree about 6½ feet tall in 1957; B, vertical section 2 to 4 feet from ground in tree 4½ feet tall in 1957. No other infection was found in either tree.

killing is less rapidly compensated by new growth; consequently, a relatively small number of well-distributed initial infections may ultimately cause serious damage to large trees even if no branch-to-branch spread occurs.

Regardless of size of the trees involved, probably less than half of the total flags resulting from a wave of spore infection are visible at any one time. While intensity of infection seems to remain fairly constant as death of old flags more or less offsets the appearance of new ones, vegetative spread of infection, i.e., by growth of mycelium instead of by spores, continues to erode crowns whether or not additional spore infections occur.

Factors affecting persistence and spread of infection. — Twig death was the principal cause of decreases in numbers of flags. Of the 1,512 twigs flagged at one time or another in the study, 69 percent died while flagged and only 21 percent were still flagged in 1965. Death of about half of the killed flags was accompanied by death of the entire branch, often including twigs that had never flagged. Although suppression contributed substantially to flag mortality, mortality rate of infected twigs was more than twice that of uninfected twigs on infected branches.

"Recovery," especially of short spurs or suppressed twigs, was sometimes attributable to absence of B needles. Often, however, B needles were present but not visibly affected. Whatever its cause, "recovery" seems in most instances to have been merely temporary disappearance of symptoms rather than elimination of infection. Mortality rate of "recovered" twigs was nearly equal to that of flagged ones, and a majority of the survivors soon relapsed. Only 17 percent of the 247 "recovered" twigs were still alive and unflagged in 1965 (several of these, however, had been "recovered" for 4 or more years).

Numbers of dead, "recovered," and new flags all varied widely from year to year, but usually consistently with each other. Figure 5 shows that:

1. In 1956, flag mortality increased and new flagging decreased.
2. In 1957, mortality decreased at John Day (the basis at Deer Creek was small) and new flagging increased.
3. In the 1959-61 period, mortality and "recovery" rose to their highest points and new flagging dropped to its lowest points on all the plots.
4. In 1962, mortality and "recovery" again decreased and new flagging increased. (Relapse of "recovered" twigs reached its peak in this year.)

Corresponding changes occurred elsewhere in the region. In 1957, a large increase in number of flags, after a slight decrease in 1956, was noted by Roth (1959) on a study area about 125 miles from the nearest of the plots discussed here. In the 1959-61 period, the disease was less conspicuous than usual on trees of all sizes in most localities. In 1959, most of the discolored needles fell much earlier than usual. In 1960 and 1961, Elytroderma fruiting was generally sparse, fewer needles than usual were discolored on flagged twigs, and many of the discolored needles were affected for less than half of their length. Such consistent fluctuations in disease trends in widely separated localities must have been caused by regional rather than purely local fluctuations in weather.

Precipitation probably has little direct effect on vegetative spread of Elytroderma, but drought increases mortality rates of diseased twigs (Childs 1960). Heat treatments are used to control several plant pathogens that are killed by temperatures their hosts can tolerate, and some evidence suggests that unusually hot seasons retard Elytroderma spread and hasten death of infected twigs:

1. The disease's greater prevalence in shaded habitats and in the upper part of the altitudinal range of its host is correlated with temperature as well as

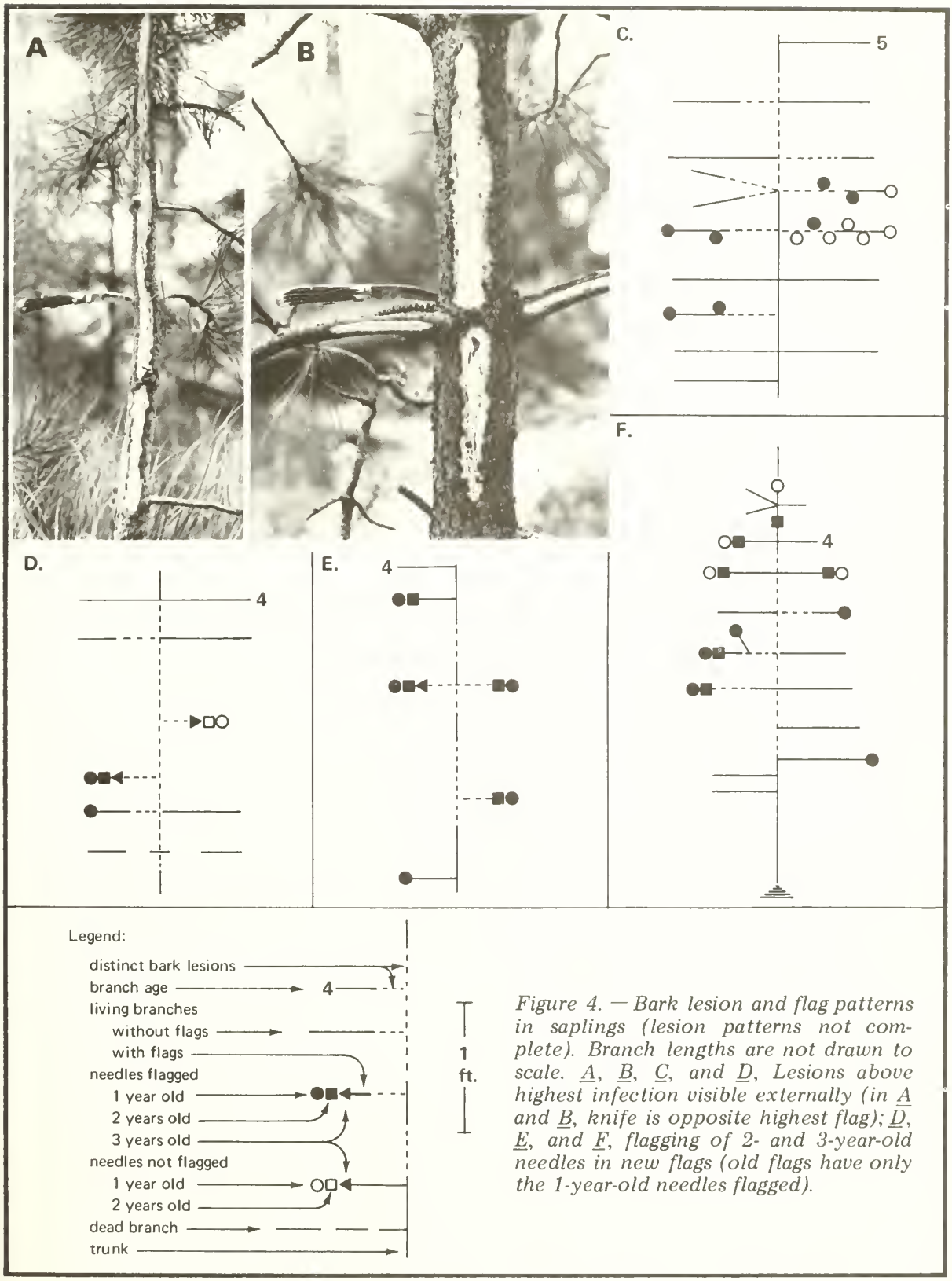


Figure 4. — Bark lesion and flag patterns in saplings (lesion patterns not complete). Branch lengths are not drawn to scale. A, B, C, and D, Lesions above highest infection visible externally (in A and B, knife is opposite highest flag); D, E, and F, flagging of 2- and 3-year-old needles in new flags (old flags have only the 1-year-old needles flagged).

moisture. In Roth's (1959) study, flags increased from 1955 to 1957 on saplings left in their original montane environment but disappeared almost completely from those moved to a lower and warmer location. "Outbreaks lasting only 1 or 2 years" have been reported (personal communications) from the Sierra Nevada in California but not from stands farther north.

2. The marked decrease in numbers of flags in the 1959-61 period followed unusually hot growing seasons in 1958 and 1960 and a relatively dry season in 1959. (Contrarily, however, the cool summer of 1955 was followed by decreases in numbers of new flags and increases in flag mortality, and recordbreaking heat in 1961 was followed by increases in new flagging and decreases in "recovery" and mortality.)
3. Decrease in number of flags during the 1959-61 period was greatest and subsequent increase was smallest on the hottest slope (John Day); at the same time the smallest decrease and greatest subsequent increase occurred on the coolest slope (Deer Creek). At John Day, decrease in number of flags was relatively greatest on southeast to southwest sides of crowns and least on northwest to northeast sides (fig. 6A). At Camas Creek it was greatest on east and southeast sides and least on northwest (fig. 6C). Changes in flag distribution on the northwest slope at Deer Creek (fig. 6B) are puzzling, but may have been caused by heat reflected from the opposite slope in this narrow valley.

Influences of weather may, of course, have been largely indirect — for example, through increasing the effectiveness of biological controls. Whatever the specific causes and their manner of action may have been, by 1961 the number of flags on the sapling plots had been reduced to a fifth of that in 1958 (table 4), and by 1965 had regained its former level only at Deer Creek (fig. 5D). After 1960, there was no increase in number of infected trees, and some of the "recovered" ones actually may have become free from infection. (Of the 68 classed as "recovered" in 1961, 38 were still unflagged in 1965.)

Though correlation of temperature with flagging is not proof of a cause-and-effect relationship, the weight of the evidence indicates that Elytroderma is more than ordinarily sensitive to climatic stress of one kind or another. Its harmlessness during the exceptionally hot, dry 1920's and 1930's therefore cannot be considered indicative of its potentialities under ordinary conditions.

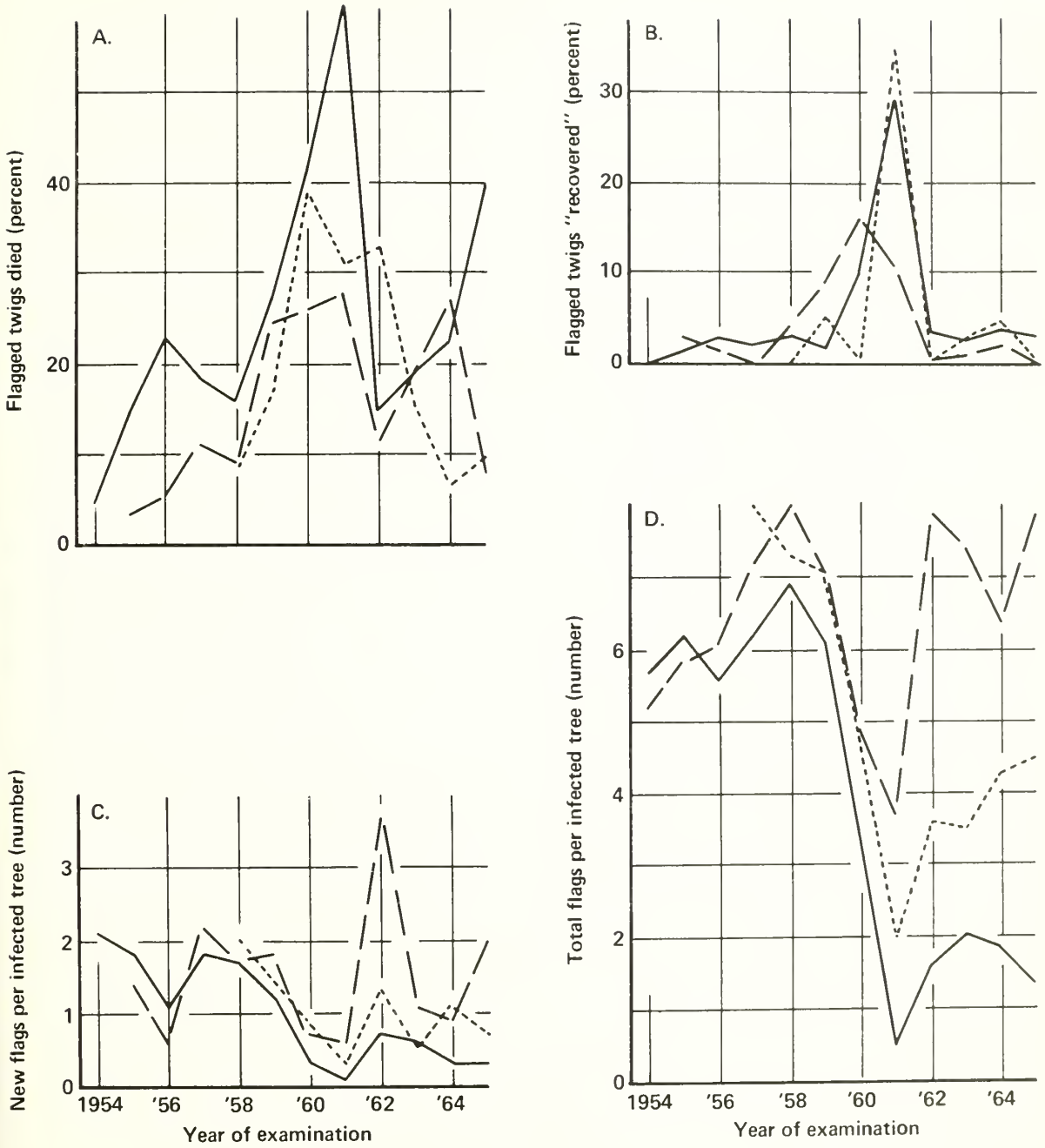
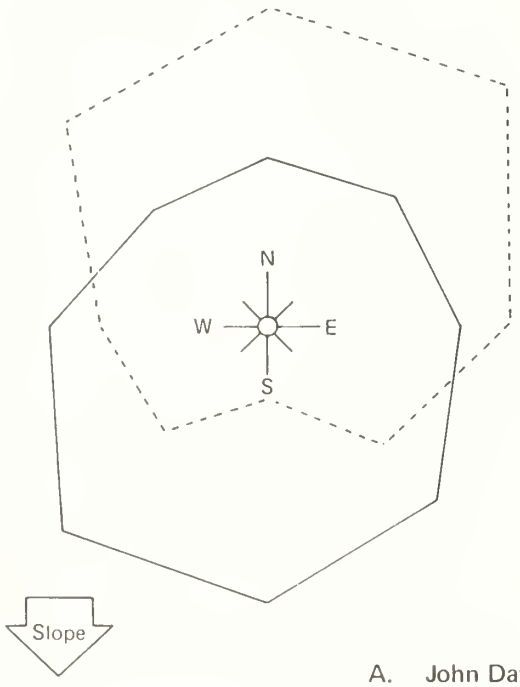
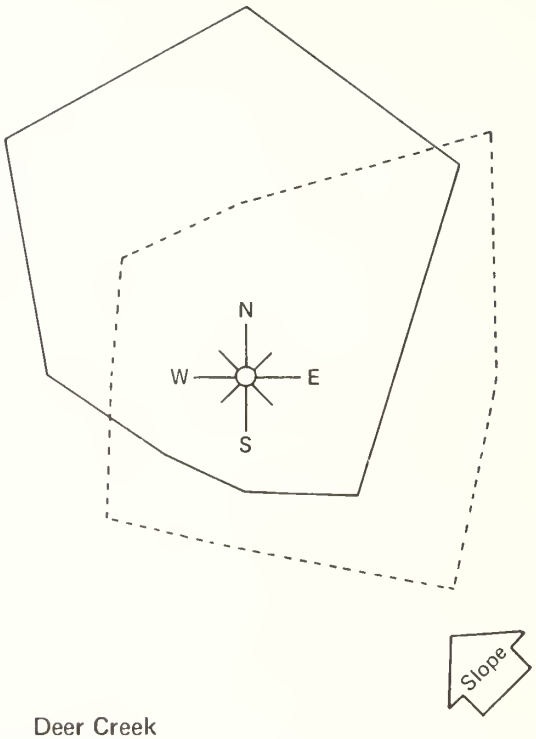


Figure 5. — Changes in flagging on sapling plots. Solid lines represent the John Day plot; broken lines, Deer Creek; dotted lines, Camas Creek.



A. John Day



B. Deer Creek

C. Camas Creek

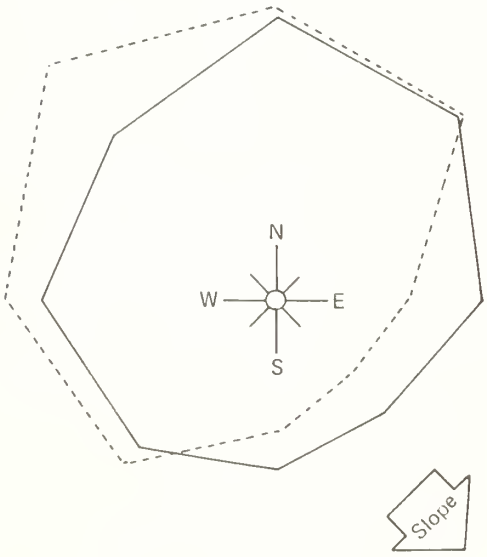
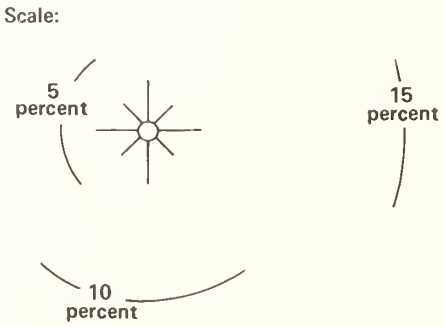


Figure 6. — Distribution of flags in 1958 (solid lines) and 1961 (dotted lines) on sapling crowns. Distances from diagram centers are proportional to percentages of total flags occurring on north, northeast, east, etc., sides of crowns (sums of distances along the eight radii equal 100 percent for each year). Arrows point downhill.



Damage to Older Stands

On the four pole plots (table 1), crop trees were marked with painted numbers and examined at 2- to 6-year intervals. Increment cores were taken from most of the survivors at Opal Flat and Chewiliken in spring of 1965.

On the two young-mature plots, all pines more than 6 inches d.b.h. at Bannon and 10 inches (including a few old-growth trees) at John Day were numbered and examined at irregular intervals (annually until 1952 at John Day). Increment cores were taken from most of the survivors at John Day in late 1955, and from all survivors at Bannon in the spring of 1965.

On the four old-growth plots, all pines more than 12 inches d.b.h. (including a few young-mature trees) were numbered and examined annually until 1952 and at irregular intervals thereafter. Increment cores were taken from most survivors except at Deer Creek in late 1955.

On all damage plots, percentages of living twigs flagged and (after 1952 or 1953) percentages of twigs dead were estimated for lower, middle, and upper thirds (by length) of each crown. D.b.h. was recorded in the first examination, and crown-condition class (Keen 1943) in the first (except at Chewiliken and Bannon) and last examinations. On the John Day and old-growth plots, estimates were also made of crown-condition classes as of about 5 years before plot establishment. Where good views were obtainable, trees on most of the plots were photographed in color at 4- to 10-year intervals.

Numbers of trees by flag-percentage classes at the first examination are shown in table 5 for each of the damage-study plots. Although lightly and heavily infected trees were intermingled to some extent, average intensity of infection differed considerably from one part of a plot to another. At Chewiliken and Bannon, infection was heaviest around grassy openings. On plots not complicated by openings or variations in stocking, infection was heaviest at the lowest end or corner:

Plot and elevation (feet)	Trees (Number)	Twigs flagged (average of first two or four examinations) (Percent)
John Day (1949-52)		
4,800-4,850	20	61
4,850-4,900	44	48
4,900-4,950	33	45
4,950-5,000	13	22
Wildwood (1949-52)		
4,800-4,850	23	10
4,850-4,900	12	5
4,900-4,950	24	1
4,950-5,000	25	1
5,000-5,150	93	1

Plot and elevation (feet)	Trees (Number)	Twigs flagged (average of first two or four examinations (Percent)
Belshaw (1951-52)		
5,100-5,150	5	81
5,150-5,200	61	53
5,200-5,250	54	42
5,250-5,300	39	32

Percentage of twigs flagged provides a rough index of infection intensity, since heavily infected trees will ordinarily bear many flags even after large parts of their crowns have been destroyed; but this percentage provides no measure of the extent to which twig killing has injured crowns. In an effort to obtain a better measure, crown damage percentages were computed from percentages of twigs flagged and percentages killed (dead twigs still present minus allowances for deaths from suppression). But this percentage, too, is only roughly proportional to total inroads of the disease. Where infection has long been present, many of the killed twigs and small branches have disintegrated, leaving no indication of time or cause of crown deterioration. (Computed percentages of crown damage sometimes decreased from one examination to another even when photographs showed that actual crown damage had increased.) Flagging and crown damage percentages are used interchangeably as convenient in the following discussion.

TABLE 5. – NUMBERS OF TREES BY INFECTION CLASSES ON DAMAGE-STUDY PLOTS

Plot	Percentages of twigs flagged at first examination									
	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
	Number of trees									
Pole plots:										
Dead Injun	76	71	52	29	13	12	14	9	5	0
Opal Flat	130	46	25	8	9	3	3	0	0	0
Austin	160	28	11	2	2	4	0	2	0	0
Chewiliken	18	22	12	18	18	14	18	9	3	0
Young-mature plots:										
John Day	12	7	13	14	13	16	17	5	9	4
Bannon	25	10	11	15	11	8	12	9	7	7
Old-growth plots:										
Grays Prairie	202	60	31	11	10	7	10	2	1	1
Wildwood	171	2	3	0	0	0	0	0	0	1
Deer Creek	50	18	11	8	5	8	2	1	0	0
Belshaw	29	16	18	16	10	16	12	26	11	5

Average flagging and crown damage percentages at different times in the study are summarized in table 6. Inclusion of trees that subsequently died would raise some of these percentages; at Belshaw, for example, average crown damage in 1952 was 47 percent for trees that survived through 1965, and 52 percent for all trees. In general, the long-term effects of the disease on the more heavily infected plots were substantially greater than appear in this table. At Belshaw, Elytroderma had destroyed probably more than 60 percent of the crown of the average surviving tree by 1964; if this plot had not been under observation for the preceding 13 years, only a little more than half of this damage could have been charged with reasonable certainty to Elytroderma.

Although the average percentages in table 6 are fairly consistent with general observations and with growth and mortality effects of the disease, they sometimes fail to show changes that are known to have occurred. At Chewiliken, for example, where many new flags were observed in 1958 and some additional ones in 1964, the 1958 estimates showed an infection increase but in 1964 the new flagging had been more than offset by death of old flags, shedding of old killed twigs, and to some extent by growth of upper crowns.

Most new flagging apparently resulted from vegetative spread of the fungus in the vicinity of infections previously observed, but appearance in occasional years of new flags widely scattered in previously uninfected upper crowns indicated that new infections by spores also occurred from time to time.

Crown condition.— Keen's (1943) crown condition classes A to D were assigned numerical values from 4 (excellent) to 1 (poor), and average ratings were computed for each plot. Decreases in crown-condition ratings on pole plots were partly chargeable to suppression of lower crowns; even on these young trees, however, heavy infection had hastened and extended the dying of the lower crown, thinned much of the remaining crown and, by reducing growth rate, retarded the formation of new crown at the top to replace that lost at the bottom.

On young-mature and old-growth plots, rapid crown deterioration occurred only where infection was moderate or heavy:

Plot	Twigs flagged at first examination	Average crown-condition ratings of trees still alive at last examination	
		First examination	Last examination
	(Percent)		
John Day	0-40	2.9	2.7
John Day	41-90	2.7	2.1
Bannon	0-40	--	2.3
Bannon	41-98	--	1.5
Grays Prairie	0-40	2.5	2.8
Grays Prairie	41-98	2.6	2.6
Wildwood	0-40	2.4	2.3
Deer Creek	0-40	2.8	2.4
Deer Creek	41-80	2.8	2.0
Belshaw	0-40	2.3	1.9
Belshaw	41-90	2.2	1.4

Crowns at John Day and Belshaw also appeared to have deteriorated appreciably (about 0.3 on the numerical scale) during the 5 years immediately preceding plot establishment.

TABLE 6. – CHANGES IN FLAGGING AND APPARENT CROWN DAMAGE ON DAMAGE-STUDY PLOTS[1]

Plots and number of trees	Year[2]							
	1950	1952	1954	1956	1958	1960	1964	All exams
	Percentage of average crown							
Pole plots:								
Dead Injun (239):								
Flagged	--	--	24	--	24	--	25	24
Damaged	--	--	31	--	46	--	42	40
Opal Flat (217):								
Flagged	--	--	12	--	8	--	12	11
Damaged	--	--	16	--	22	--	20	19
Austin (199):								
Flagged	--	--	7	--	5	--	2	5
Damaged	--	--	13	--	29	--	25	23
Chewiliken (99):								
Flagged	--	--	--	29	44	45	30	37
Damaged	--	--	--	35	47	55	49	46
Young-mature plots:								
John Day (90):								
Flagged	43	42	26	28	18	--	14	28
Damaged	--	--	39	39	39	--	25	36
Bannon (87):								
Flagged	--	--	--	34	48	36	29	37
Damaged	--	--	--	38	52	45	44	45
Old-growth plots:								
Grays Prairie (322):								
Flagged	13	10	8	--	6	--	16	11
Damaged	--	20	14	--	16	--	25	19
Wildwood (158):								
Flagged	2	1	2	--	2	--	2	2
Damaged	--	7	10	--	11	--	10	9
Deer Creek (95):								
Flagged	--	22	21	21	21	--	11	19
Damaged	--	33	33	30	--	--	20	29
Belshaw (105):								
Flagged	--	37	29	24	17	--	23	26
Damaged	--	47	46	38	38	--	35	41

[1] *Includes only trees still alive at last examination. Excludes a few trees pruned, deformed, heavily infected by dwarf mistletoe, or with tops girdled or badly broken.*

[2] *Several percentages are combined from estimates made in 2 or occasionally 3 successive years, and a few are from single examinations made 1 year before or after the indicated date.*

Uncrowded saplings and poles with badly damaged crowns but good tops can recover fairly rapidly through upper-crown growth, but probably remain, for more than a decade, highly susceptible to the various parasites that prey on weakened trees. Larger trees, especially old-growth, do not repair damaged crowns rapidly. In sawtimber stands, even a single wave of Elytroderma infection contributes, proportionately to its severity, to more or less permanent deterioration of crowns and consequent reduction of growth and increase in vulnerability to bark beetles and other enemies.

Growth rate. — Growth data from Chewiliken increment cores were analyzed in greater detail than those from other plots. Table 7 shows that:

1. Correlations of d.b.h. with crown damage (column 3; variables B to E) were so small and lacking in statistical significance that they can be ignored.
2. Correlations of d.b.h. with 1955-59 and 1960-64 ring widths (column 3; variables M and N), although significant at the 5-percent level in the latter instance, were not great enough to invalidate comparisons between groups of trees differing moderately in average size.
3. Correlations of the four expressions of total crown damage (variables B to E) with 1955-59 and 1960-64 ring widths (columns 4 and 5) were all significant at the 1-percent level, but the maximum estimate (D) and the average of all estimates (E) each accounted for about one-fourth more of the variability in ring width than did either the 1956 or 1965 estimate alone.
4. Correlation of 1955-59 and 1960-64 ring widths with crown damage were improved only slightly by inclusion of upper-crown damage as another independent variable (variables M and N; columns 6 and 7).
5. Correlations of crown damage with ring width was also significant at the 1-percent level for the period 1950-54, but was not statistically significant for any of the preceding 5-year periods (column 6; variables G to L).

Elytroderma's depressing effect on diameter growth[13] is shown in column 8 of table 7, in figures 7 and 8, and in tables 8, 9, and 10. Although it is evident that the effect of the disease on growth became greater with passage of time, the data do not permit conclusions as to how much of the increase in effect is due to increase of infection and how much to cumulative impact of a constant intensity of infection over a period of several years.

Other complications also interfere with definite evaluations of the disease's effects on growth. For reasons previously given, flagging and crown damage percentages cannot be considered accurate measures of the inroads of the disease on crowns. In the small samples available, Elytroderma effects could not be clearly distinguished from effects of other factors. Root diseases (discussed further under "Mortality") apparently caused substantial reductions of growth rates in some instances — for example, in the five lightly to moderately infected trees represented by the broken line in figure 8B. Since Elytroderma is almost always most abundant in lower parts of crowns, light to moderate infection probably has more effect on mature trees than on poles, whose lower branches contribute little to tree nutrition.[14]

[13] *Growth measurements were corrected for missing rings and for rare false rings by methods used by Keen (1937), McGinnies (1963), and others, and described in the appendix. The effect of the disease on growth was evident, however, before corrections were made.*

[14] *Pruning studies (Helmers 1946, Stein 1955) have shown that removal of the bottom quarter of live crown of young conifers has little or no effect on growth. However, diseased lower branches are perhaps net liabilities to the tree, rather than merely worthless.*

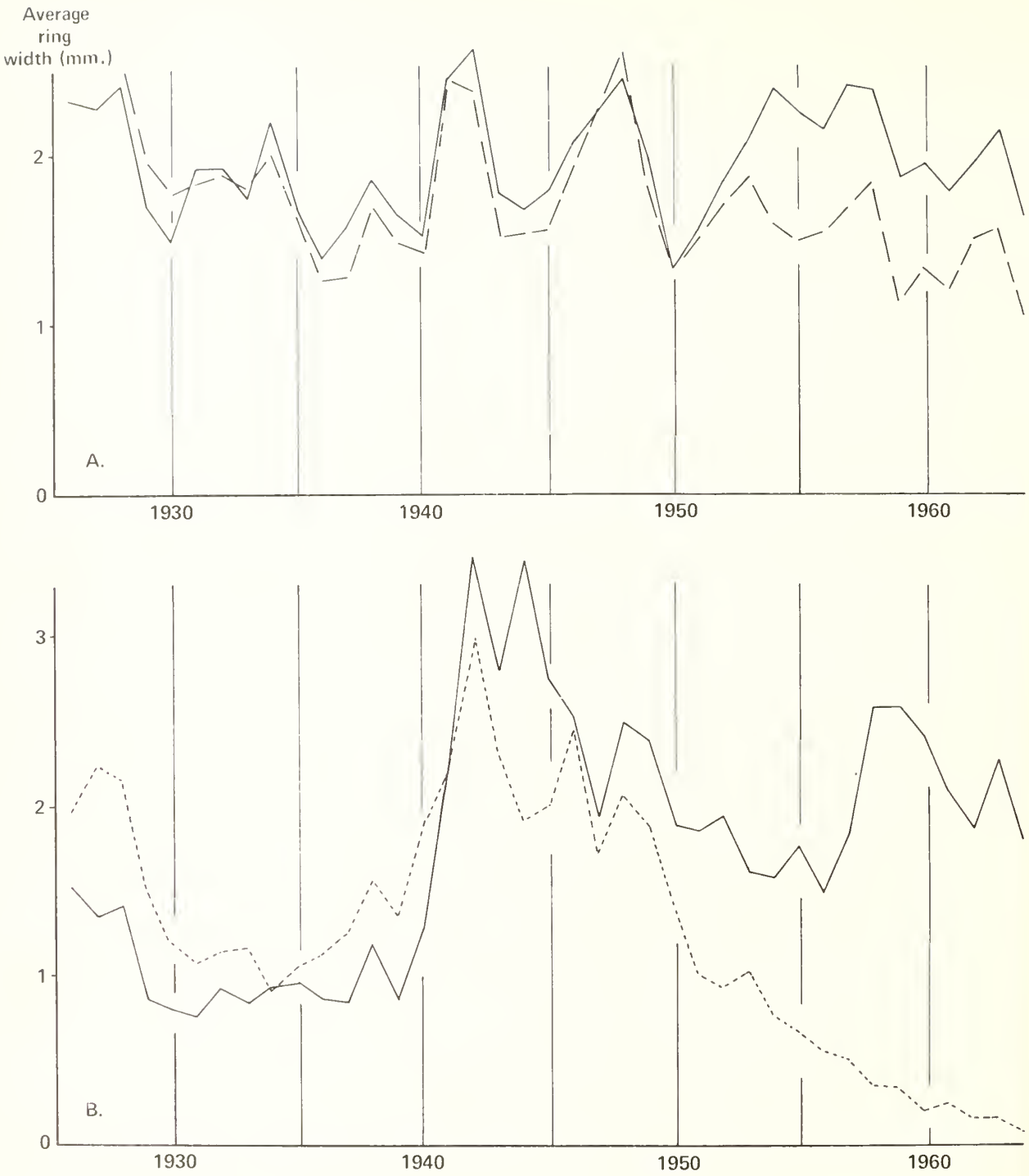


Figure 7. — Effect of Elytroderma infection on diameter growth in selected tree classes in pole stands. Solid lines represent light infection; broken line, moderate; dotted line, heavy. A, Opal Flat: 16 uninfected or lightly infected trees compared with eight moderately infected trees (the most heavily infected on this plot) of the same diameters (additional details in table 8); B, Chewiliken: the four most lightly infected trees (average crown damage 13 percent) compared with the nine most heavily infected surviving trees (average crown damage 76 percent).

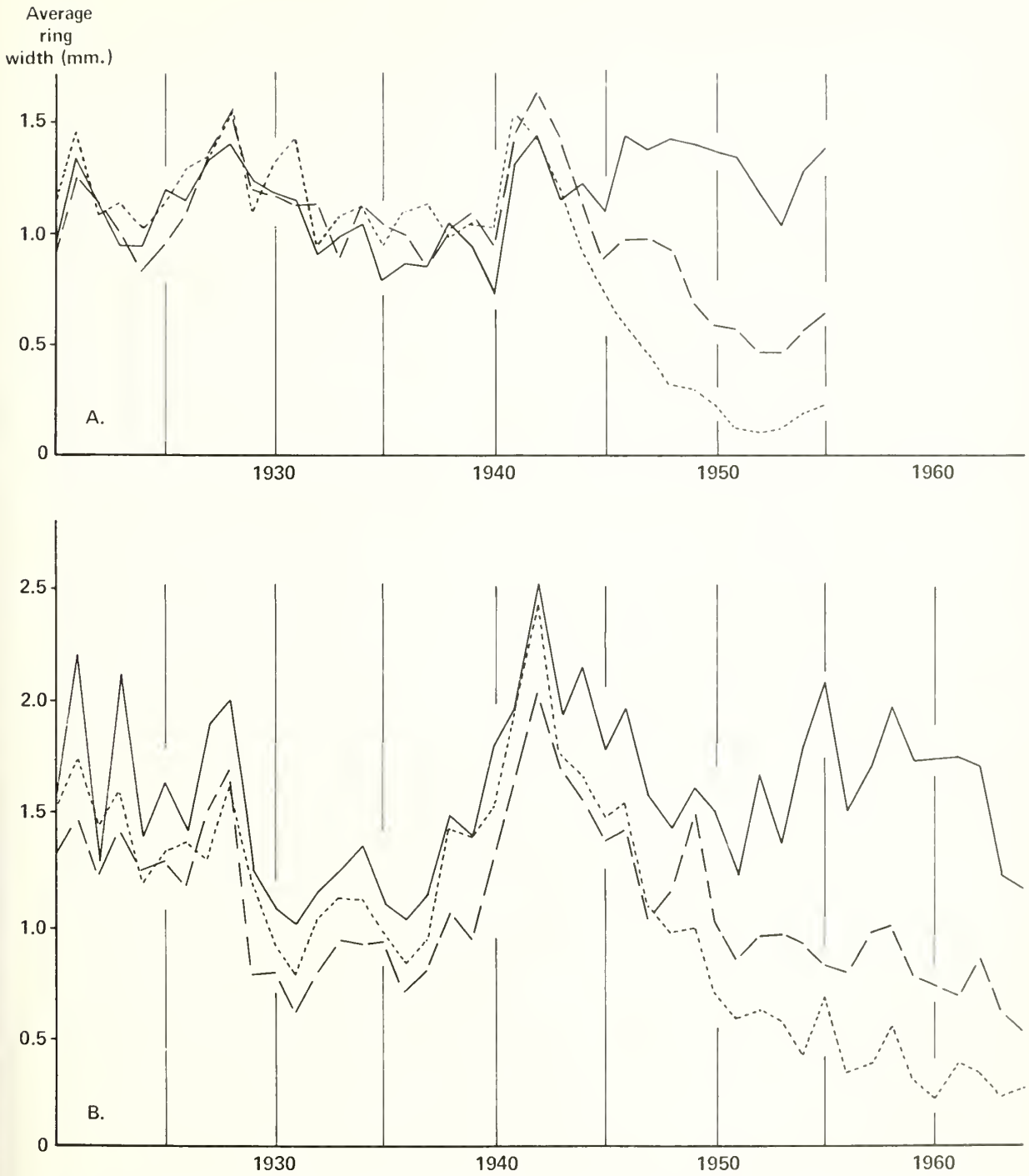


Figure 8. — Effect of Elytroderma infection on diameter growth in selected tree classes in young-mature stands. Solid lines represent light infection; broken lines, intermediate; dotted lines, heavy. A, John Day: trees with little or no dwarf mistletoe and 1921-30 average ring widths between 1.0 and 1.5 mm. (additional details in table 9); B, Bannon: four very lightly infected trees (average crown damage 6 percent) compared with five lightly to moderately infected (average damage 24 percent) and four heavily infected (average damage 71 percent) (all trees 15.1 inches d.b.h. or larger).

TABLE 7. – COEFFICIENTS BASED ON 94 CHEWILIKEN TREES STILL ALIVE AND AT LEAST 50 YEARS OLD IN 1965

Variable	Mean	Coefficient of					
		Simple correlation with variable--			Partial[1] correlation with variable--		Regression[1] on variable--
		A	M	N	E alone	E and F	E
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
A. D.b.h.	8.9 inches	1.0000	0.1833	0.2266[2]	--	--	--
B. 1956 estimate of total crown damage	34.7 percent	-.0245	-.6152[3]	-.6228[3]	--	--	--
C. 1965 estimate of total crown damage	51.4 percent	-.1294	-.5417[3]	-.6995[3]	--	--	--
D. Maximum estimate of total crown damage	59.8 percent	-.1079	-.6515[3]	-.7545[3]	--	--	--
E. Average estimate of total crown damage	47.6 percent	-.0773	-.6578[3]	-.7441[3]	1.0000	--	--
F. Average estimate of damage to upper crown	12.2 percent	--	--	--	.8594[3]	--	--
G. 1925-29 annual-ring width	10.5 mm.	--	--	--	.1584	--	0.034
H. 1930-34 annual-ring width	5.7 mm.	--	--	--	.1323	--	.020
I. 1935-39 annual-ring width	6.8 mm.	--	--	--	.0248	--	.004
J. 1940-44 annual-ring width	13.3 mm.	--	--	--	-.0603	--	-.018
K. 1945-49 annual-ring width	12.2 mm.	--	--	--	-.1973	--	-.052
L. 1950-54 annual-ring width	8.3 mm.	--	--	--	-.4368[3]	--	-.103
M. 1955-59 annual-ring width	5.5 mm.	.1833	1.0000	.8464[3]	-.6578[3]	-0.6602[3]	-.136
N. 1960-64 annual-ring width	4.0 mm.	.2266[2]	.8464[3]	1.0000	-.7441[3]	-.7492[3]	-.139

[1] *D.b.h. held constant.*

[2] *Significant at 5-percent level.*

[3] *Significant at 1-percent level.*

TABLE 8. – EFFECTS OF CROWN DAMAGE BY ELYTRODERMA ON DIAMETER GROWTH IN POLE STANDS

Plot and d.b.h. class (inches)	Average	Crown damage[1]			Tree basis	1925-29	1930-34	1935-39	1940-44	1945-49	1950-54	1955-59	1960-64	Average width of narrowest ring present[2]	Rings missing[2] in trees	
		Total Crown		Upper crown average												
		Range	Average												Rings	Trees
	Inches	*-----Percent-----*			*Number*	*-------Percent of growth of lightest infection class-------*								*Mm.*	*---Number---*	
Opal Flat																
(10.1-18.0)	13.4	0-14	5	< 1	16	100	100	100	100	100	100	100	100	1.01	0	0
	13.4	32-50	37	5	8	116	100	90	93	96	87	69	70	.74	0	0
Chewiliken[3]																
(6.1-9.0)	7.5	9-30	23	1	7	100	100	100	100	100	100	100	100	1.16	0	0
	7.6	31-50	41	6	21	111	98	101	99	74	71	54	55	.56	4	2
	8.0	51-66	58	16	16	108	104	92	94	76	64	37	24	.31	21	6
	7.1	72-80	76	39	7	114	108	108	85	74	50	28	12	.12	27	4
(9.1-12.0)	10.5	14-29	23	< 1	7	100	100	100	100	100	100	100	100	1.24	0	0
	10.6	31-49	39	4	8	118	120	110	111	107	89	66	62	.84	2	1
	10.3	51-69	60	19	14	125	116	114	119	97	62	36	28	.38	24	7
	10.1	74-80	77	44	2	105	117	62	89	48	26	10	6	.26	16	2

[1] *Average of all examinations.*

[2] *Since 1940.*

[3] *Trees at least 50 years old in 1965.*

TABLE 9. – EFFECTS OF FLAGGING BY ELYTRODERMA ON DIAMETER GROWTH IN YOUNG-MATURE STANDS

Plot	Average ring width 1921-30	Twigs flagged[1]		Tree basis	1921-25	1926-30	1931-35	1936-40	1941-45	1946-50	1951-55	1956-60	1961-65	Average width of narrowest ring present[2]	Rings missing[2] in trees	
		Class	Average												Rings	Trees
	Mm.	*---Percent---*		*Number*	*----------Percent of growth of lightest infection class----------*									*Mm.*	*---Number---*	
John Day[3]	> 1.5	< 30	18	11	100	100	100	100	100	100	100	--	--	1.24	0	0
		30-60	45	10	96	100	116	101	101	84	48	--	--	.55	2	1
		> 60	86	1	153	71	26	23	28	1	< 1	--	--	.08	9	1
	1.0-1.5	< 30	11	6	100	100	100	100	100	100	100	--	--	.86	0	0
		30-60	45	12	93	101	106	112	105	58	43	--	--	.42	18	4
		> 60	71	3	105	105	113	120	93	26	12	--	--	.07	0	0
	0.5-1.0	< 30	16	11	100	100	100	100	100	100	100	--	--	.45	0	0
		30-60	44	13	105	99	103	76	84	41	35	--	--	.15	21	9
		> 60	82	5	97	97	121	125	93	25	7	--	--	.13	31	5
	< 0.5	< 30	13	6	100	100	100	100	100	100	100	--	--	.36	0	0
		30-60	46	4	105	96	212	248	172	86	45	--	--	.17	4	2
		> 60	84	1	103	79	106	110	83	7	7	--	--	.04	4	1
Bannon[4]		< 30	16	9	--	100	100	100	100	100	100	100	100	.63	0	0
		30-60	41	11	--	91	103	112	103	113	89	71	71	.52	3	2
		> 60	71	4	--	93	101	108	102	83	48	35	27	.16	21	2

[1] *Average of all examinations up to year of growth measurement (Bannon figures are crown damage percentages).*

[2] *Since 1940.*

[3] *Exclusive of a few trees with moderate or heavy dwarf mistletoe infection.*

[4] *Trees more than 15 inches d.b.h. (not classified by ring width). Growth at Bannon is for periods 1925-29, 1930-34, etc.*

TABLE 10. – EFFECTS OF FLAGGING BY ELYTRODERMA ON DIAMETER GROWTH IN THE OLD-GROWTH STAND AT BELSHAW

Average ring width 1921-30 (mm.)	Twigs flagged[1]		Tree basis	1921-25	1926-30	1931-35	1936-40	1941-45	1946-50	1951-55	Average width of narrowest ring present[2]	Rings missing[2] in trees	
	Class	Average										Rings	Trees
	Percent		*Number*	*Percent of growth of lightest infection class*							*Mm.*	*Number*	
>1.5	<30	20	8	100	100	100	100	100	100	100	0.67	4	1
	30-60	45	7	117	119	134	144	136	89	90	.64	12	2
	>60	70	6	89	102	94	109	87	30	20	.26	26	4
1.0-1.5	<30	15	10	100	100	100	100	100	100	100	.43	5	1
	30-60	49	10	91	103	105	132	144	78	42	.18	10	4
	>60	72	5	95	97	84	88	81	13	<1	.17	42	5
0.5-1.0	<30	13	33	100	100	100	100	100	100	100	.36	16	4
	30-60	51	12	94	94	121	107	93	59	35	.19	38	9
	>60	65	3	102	107	89	100	77	38	4	.27	26	3
<0.5	<30	13	15	100	100	100	100	100	100	100	.15	19	7
	30-60	49	13	111	113	100	104	115	62	43	.13	72	10
	>60	71	6	89	83	76	79	68	42	5	.07	47	6

[1] *Average of all examinations up to 1955.*

[2] *Since 1940.*

It may nevertheless be concluded, with due qualifications, that impact of Elytroderma on tree growth is proportional to extent of crown damage. This impact appears to be affected only slightly by age (compare tables 8, 9, and 10) or by vigor prior to infection (compare the different 1921-30 growth rate classes in tables 9 and 10).

Because of Elytroderma's persistence and vegetative spread, its impact on growth continues for several years, even in young trees. Most young trees probably recover eventually from fairly severe infection provided they escape other enemies, but growth-rate reductions as large and long-lasting as those shown in figure 7 and table 8 will considerably lengthen rotations.

Although volumes added by annual growth are less important in young-mature stands and of practically no importance in old growth, rates of growth in such stands are of interest because of their relationship to mortality risk. This relationship may sometimes be merely associative — that is, reduced growth may be only a symptom of a physiological weakening that predisposes the tree to disease or insect attack — but it may sometimes be causative. For example, resistance to certain root diseases probably depends in part on the rapidity with which the tree can form new roots or effective callus barriers on old roots. Whatever the relationship may be, slowly growing trees are notoriously poor mortality risks.

Mortality. — Field determinations of causes of deaths on the damage plots (table 11) are only roughly indicative of Elytroderma's mortality effects, since the disease was undoubtedly involved in some of the deaths charged to other causes — and, conversely, since some deaths charged to Elytroderma probably resulted from combinations of factors no one of which would have been fatal, or at least so quickly fatal.

Root disease effects, especially, could not be separated from those of Elytroderma. General observations during this and other studies suggest that root diseases most readily attack weakened trees and then often spread vegetatively to more vigorous neighbors. If this is true, Elytroderma may have indirectly caused death of some trees that it had infected only lightly. Well-known and fairly obvious root rotters such as *Armillaria mellea* and *Fomes annosus* appeared no more damaging where Elytroderma was abundant than elsewhere. However, an obscure and previously unobserved disorder, probably a disease of small roots, caused much crown deterioration and killed several trees at Bannon, on part of the Chewiliken plot, and perhaps also at Dead Injun, John Day, and Belshaw.

Although there is no way of knowing what mortality would have occurred on the damage plots if Elytroderma had not been present, it is evident from table 12 that heavy Elytroderma infection was associated with high mortality rates.[15] Whether killing was direct or indirect is of little importance. Annual mortality rates averaged 0.25 percent or less on plots where infection was generally light (Opal Flat, Austin, Grays Prairie, and Wildwood), but more than 2 percent where infection was heavy (Chewiliken, Bannon, and Belshaw). On all plots, mortality rates were highest in trees of the heaviest infection and poorest crown-condition classes. Similar results were obtained from plots in Idaho (see Appendix).

Mortality was nearly as common in large size-classes as in small. At Chewiliken, average d.b.h. was 8.7 inches for surviving trees and 8.2 for dead ones (again exclusive of trees windthrown); at Bannon, 13.1 and 11.4 inches; and at Belshaw,

[15] *Trees knocked down or windthrown are not included as mortality in this table, since their death could in no way be attributed to Elytroderma (except possibly through the effect of the disease on stand density). Mortality from all other causes is included since Elytroderma was a possible contributing factor in most instances.*

TABLE 11. — MORTALITY ON DAMAGE PLOTS, BY CAUSE

Item	Dead Injun	Opal Flat	Austin	Che-wiliken	John Day	Bannon	Grays Prairie	Wild-wood	Deer Creek	Belshaw
	Number of trees									
Alive at start of study	281	224	209	132	110	115	335	177	103	159
Death attributed to:										
Elytroderma	7	0	4	21	12	19	2	1	0	35
Root diseases	13	0	0	3	2	3	0	2	5	2
Beetles	2	0	0	0	4	0	2	2	0	5
Canker	0	0	0	2	0	0	0	0	0	0
Fire	0	0	0	2	0	0	0	0	0	0
Cut	0	2	0	0	0	0	4	0	1	3
Knocked or blown down	9	2	0	0	2	0	4	11	0	5
Unknown	0	3	0	0	0	0	1	2	1	4
Total dead	31	7	4	28	20	22	13	18	7	54
Contributing cause of death:										
Elytroderma	12	0	0	4	3	0	1	0	0	1
Root diseases	2	0	0	2	1	4	0	1	0	10

TABLE 12. – MORTALITY[1] ON DAMAGE-STUDY PLOTS

Plot	Crown condition class[2]	Total trees in infection class[3]				Trees died during study in infection class[3]				All classes	Length of study
		0-30	31-60	61-80	81-100	0-30	31-60	61-80	81-100		
		Number				*Percentage*				*Percent*	*Years*
Dead Injun	Good	168	48	17	5	4	0	12	40		
Dead Injun	Fair	27	6	6	0	15	50	33	--	8	9
Dead Injun	Poor	4	0	0	0	50	--	--	--		
Opal Flat	All	201	20	3	0	1	5	33	--	2	10
Austin	All	199	8	2	0	0	25	100	--	2	10
Chewiliken	All	52	50	27	3	8	8	63	100	21	9
John Day	Good	18	28	11	2	0	4	18	0		
John Day	Fair	14	13	9	5	7	15	33	40	16	17
John Day	Poor	0	2	2	6	--	100	50	67		
Bannon	All	46	34	21	14	7	9	33	64	19	9
Grays Prairie	All	293	28	12	2	2	7	0	50	3	16
Wildwood	All	176	0	0	1	3	--	--	100	4	16
Deer Creek	All	79	21	3	0	9	0	0	--	7	14
Belshaw	Good	18	14	4	0	6	0	25	--		
Belshaw	Fair	37	21	18	4	19	14	33	100	31	15
Belshaw	Poor	8	7	16	12	38	71	56	92		

[1] *Exclusive of trees knocked down or windthrown.*

[2] *At first examination. "Good" is Keen's (1943) classes* A *and* B; *"fair," class* C; *and "poor," D.*

[3] *Percentages of twigs flagged at first examination.*

23.8 and 20.5 inches. In general, trees killed by Elytroderma had grown more slowly than survivors (appendix table 13), not only since attack by the disease but also during the 1920's and 1930's. It is reasonable to assume that a given percentage of crown damage by the disease is most injurious to trees whose crowns are already in poor condition or whose growth rate has been reduced by other adverse factors.

Heavily infected trees are sometimes surprisingly tenacious of life. For example, when the John Day damage plot was established, two very heavily infected trees appeared unlikely to survive for more than a year; one of these trees survived for 7 years, and the other was still alive and apparently in slightly improved condition after 17 years. On this same plot, a tree 15 inches in d.b.h. had only seven living twigs in 1951 but survived until 1956, presumably because it was root-grafted to a less badly damaged neighbor.

Even though some heavily infected trees survive for many years, infection intensities like those at Chewiliken, Bannon, and Belshaw cannot long be tolerated in valuable stands.

Control

Lightle (1955) tested several chemicals but found neither surface nor penetrating fungicides to be effective against Elytroderma. Tests of systemic (penetrating) fungicides[16] in two Oregon localities were also unsuccessful, regardless of method (basal spray or foliage spray) or season of application. Some treatments, especially with stove oil as the vehicle, caused severe defoliation and some mortality, but surviving trees had the same twigs flagged after recovery from defoliation as before treatment.

Since injury by Elytroderma results largely from vegetative persistence and spread of infections, the disease seems highly vulnerable to chemical control if an effective eradicant suitable for aerial application can be found. At present, little can be done to reduce damage except to put young stands in thrifty condition, and to salvage threatened mature trees before they die.

Efficient salvage is not just a matter of harvesting moribund trees. The usual practice in ponderosa pine is to log all trees in poor condition but only enough of those in fair condition to bring the cut up to 30 or 40 percent of total stand volume. In Elytroderma-damaged stands, even where average infection was no more than moderate, such cuts have invariably been followed by rapid deterioration of residual crowns, necessitating relogging within a year or so. Additional cuts in quick succession have sometimes been necessary, leaving areas practically clearcut or with residual stands composed almost entirely of species other than ponderosa.

[16] *Phytoactin (provided by P-L Biochemicals, Milwaukee, Wis.) at concentrations of 200 and 400 parts per million in water, and various formulations of Actidione (provided by Upjohn Company, Kalamazoo, Mich.) at concentrations of 50 and 100 parts per million in water and in stove oil.*

Deterioration of residuals is fairly common in seemingly healthy stands and very common where diseases are prevalent. Like "shock" from thinning in young stands (Staebler 1956), this deterioration is probably caused by sudden and drastic environmental change which cannot be tolerated by trees already weakened.

Salvage of occasional dead and dying trees probably causes little damage to the remaining stand, since disturbance will be slight and some opening of the stand will occur whether the trees are removed or not. Where Elytroderma has made substantial inroads on the crowns and repeated cuts at short intervals would increase logging costs, it appears advisable to (1) postpone salvage until heavy mortality is imminent, beetle populations are increasing dangerously, or the stand is reached in the course of normal operations; and then (2) take all ponderosa pines except those of very good vigor (Keen classes A or B+) with no more than about 5 percent of the twigs flagged. On one of the last large salvage operations in a stand heavily infected by Elytroderma, more than 80 percent of the volume was cut and the remaining stand has continued in excellent vigor.

Discussion

Weir (1916) states that "average size of the brooms is about 2 feet in diameter" and "on large and mature trees *H. deformans* very rarely occurs on any part of the tree except the needles of these brooms." Since brooms from the present outbreak, approximately 25 years after it started, still average less than 2 feet in diameter, and since unbroomed flags are still common in large trees, the outbreak described by Weir must have started about 1890 or earlier. Furthermore, for several years prior to his observations, there seems to have been little or no spread of infection in large trees, either vegetatively or by spores, even though most years from 1900 to 1915 were moister than normal (Keen 1937).

Weir's observations were made too late in the outbreak to permit determination of the extent to which Elytroderma was responsible for crown damage and mortality, undoubtedly still evident at that time in pole and mature stands. Although he describes distribution and impact of the disease only in general terms, his report suggests that, as in the present outbreak, infection was common in many stands but seriously damaging in only a few.

Except for infection on lodgepole pine in one locality and old brooms, Elytroderma was not recorded again in Oregon and Washington for 30 years.

In 1945, when the current outbreak was first noticed, damage was already obvious on several hundred acres. Increment core measurements later showed that growth rates of some heavily infected trees had been reduced by 1944 and possibly as early as 1942. The disease evidently was present for some time prior to 1945, but was overlooked probably because of wartime diversion of forestry efforts.

Growth-rate comparisons indicate that the outbreak started at about the same time, both in Washington and Oregon, in all stands where appreciable damage was later caused. Growth of trees in moderately infected stands sometimes showed no effects until several years after 1944, but the same was true of moderately infected trees in heavily infected stands. Time from spore infection to flagging can hardly be less than a year, and Evenden (1940) found no retardation of basal growth of mature ponderosa pine until 1 year after "considerable foliage was destroyed." Therefore, even if the outbreak started with a wave of spore infections that gave rise directly to immense numbers of flags, this wave could not have occurred later than spring of 1942.

Origin of the outbreak in an initial wave of such magnitude is questionable. Elytroderma is poorly adapted for long-distance spread of infection in quantity, and local sources of infection were rare almost everywhere during the years just before the outbreak (although infection of lodgepole pine, where effects of this disease are less conspicuous, may have been more common than records indicate). It seems more likely, then, that great numbers of flags resulted from vegetative spread of the fungus from relatively moderate numbers of spore infections, or perhaps that a preliminary, moderate wave of infection provided sources of spores for a somewhat later major wave.

The main wave of infection by spores probably occurred no earlier than 1938 because (1) normal precipitation in eastern Oregon in 1938 was preceded by several dry years, when periods favorable for Elytroderma infection were presumably even rarer than in average or wet years; and (2) flagging from moderate or heavy infection that occurred before 1938 would undoubtedly have attracted attention while foresters were still engaged in peacetime activities.

During the last 15 or 20 years, intensification of infection appears to have been principally by vegetative spread along branches and, at least for short distances in small trees, along trunks. Additional infections by spores were common in occasional years, causing scattered flagging at considerable distances from original outbreak centers and increasing the severity of damage at the original centers. However, despite great numbers of spores produced and generally near-average precipitation since the early 1940's, damage by subsequent spore infections has probably been less than damage from the wave that occurred about 1940.

So much is still unknown about this disease, and especially about conditions governing origin and intensification of outbreaks, that prophecy is risky. Nevertheless, the facts available from later stages of two outbreaks provide some basis for predicting future behavior of Elytroderma.

Probably then, the current outbreak will continue its present slow abatement until its only evidences are unusually high percentages of poor-crowned trees in occasional stands, and old brooms and a few scattered flags here and there. After an indefinite period at this low level, the disease will again become conspicuous, simultaneously and perhaps suddenly in localized centers of heavy infection and gradually and less severely elsewhere. Within a few years, mortality rates will increase in moderately to heavily infected mature stands and in heavily infected pole stands, but severe damage will be confined almost entirely to the original centers of the new outbreak. After a decade or more, the cycle will be completed as flagging again decreases slowly in abundance.

Because of Elytroderma's marked topographic preferences, many of the centers of the current outbreak presumably were also centers of previous outbreaks. Yet previous outbreaks in these centers did not prevent (although they no doubt retarded) the development of mature stands that contained good volumes

of ponderosa when the current outbreak started. Previous outbreaks may, of course, have been less severe than the current one — but the current one has been no more than moderately damaging to originally thrifty young stands.

The disease is obviously too important to be ignored, but its importance has sometimes been overrated because of the sudden appearance and alarming aspect of the current outbreak. According to recent estimates, it causes less than 3 percent of the total damage by disease to ponderosa pine in this region. *Elytroderma deformans* is a native fungus, an inhabitant of ponderosa pine forests through countless forest generations. The balance that has developed between fungus and host is less stable than is usual with native fungi; but even where most favored by environmental conditions, the fungus does not threaten to eliminate its host as a commercial species. Like other normal hazards such as fire and beetles, the Elytroderma disease merits the forester's respectful attention but is no cause for dismay.

Recommendations

Young stands. — Since frequency and extent of future outbreaks cannot now be predicted, forest managers must rely on personal judgment in deciding how much weight to give the disease in management plans. Where infection during the current outbreak has been light, the disease is unlikely to be seriously damaging in the future. At the other extreme, stagnated stands on and near former outbreak centers are likely to be damaged by another outbreak before they mature. In such situations, Elytroderma disease may be one of the most important factors to be considered.

Thinning and pruning are too expensive by present methods to be justifiable solely for control of Elytroderma, but their probably mitigating effect on the disease is one of the benefits to be balanced against their costs in economic analyses of stand improvement. Greater investment risk where disease hazard is high must, of course, also be taken into account.

To minimize damage by infection now present or likely to occur before the stand matures:

1. Maintain good spacing. Infection is heaviest on crowded trees and most injurious to slowly growing ones. Large openings in the stand apparently make the environment more favorable for spread of the disease by spores.
2. Select no crop trees flagged within 3 feet and preferably none flagged within 6 feet of the leader. Infections near the leader often spread to it, and small trees with infected leaders seldom develop into anything better than "coniferous brush."
3. Select uninfected or only lightly infected crop trees, even at a considerable sacrifice of present tree size and quality. Flags visible during early stages of outbreaks are only a small fraction of those that will eventually result from

vegetative spread of infections already established. Infection in trunks of small trees deforms them at least temporarily, and perhaps permanently.

4. Prune where returns will equal investment plus carrying costs. The great majority of spore infections occur in lower crowns, where they produce quantities of spores for further spread, and from which they may invade and injure trunks and spread vegetatively for undetermined distances into higher branches.
5. Do not be bluffed by the disease. Where good pine has once grown, good pine can grow again.

Mature stands. — Future outbreaks will undoubtedly cause some damage even in vigorous young-mature stands and more severe and rapid damage in decadent over-mature stands. Since most pine stands are now fairly accessible, salvage difficulties are managerial and silvicultural rather than physical. The problem is to save threatened values without harm to the remaining stand and with minimum disruption of normal operations.

When the disease becomes conspicuous in mature stands:

1. Do not take hasty action. Appreciable damage will not occur for at least a few years after the outbreak starts. New flags in vigorous crowns are striking in appearance — much more so than killed twigs and old faded flags in poor crowns — but are not indicative of greatly reduced growth and imminent mortality.
2. Evaluate the situation annually on the basis of examinations made in spring and early summer, when flags are easiest to see and identify. Assume that:
   a. Flagged twigs will die within a few years.
   b. Additional flagging will occur — probably more than twice as much, ultimately and for the stand as a whole, as is visible during early outbreak stages.
   c. Trees with half of their twigs flagged or killed are likely to be attacked by bark beetles or root diseases, and trees with more than three-fourths of their twigs flagged or killed are likely to die as a direct result of defoliation.
   d. Trees with originally poor crowns will be damaged more rapidly and severely than equally infected trees with originally good crowns.
3. Revise logging plans to give higher priority to stands where appreciable damage is to be expected within the next few years, and to provide for immediate logging wherever mortality rates or beetle populations start to increase.
4. When logging in lightly infected stands, remove the occasional tree that may be found with more than a third of its twigs flagged or killed and discriminate as much as is practicable against the most heavily infected of the other trees.
5. When logging in moderately or heavily infected stands, either cut drastically, leaving only trees with very good (Keen class A or B+) crowns and no more than a few scattered flags, or plan to relog within a year or so if necessary. Partial cuts in diseased stands are usually followed by rapid crown deterioration and high mortality of residuals.

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Appendix

Estimating flagging and twig killing. — Although Elytroderma flags have a fairly distinctive color, it was occasionally impossible to make satisfactory estimates because of exceptional abundance of other foliage diseases. A few trees were chronically discolored by other diseases, and some were so screened by other trees that little of the crown could be seen clearly. Nevertheless, by use of various safeguards, estimates were obtained that proved in most instances to be accurate enough for purposes of this study.

Examinations were made between late May and early July, before the flags faded. Since the disease is not equally distributed on all sides of a crown, trees were viewed from opposite sides whenever practicable. Flagging can be seen best when the sun is behind or to the side of the observer. When crowns were silhouetted against an overcast sky, making flags hard to see, examinations were postponed or crowns were viewed through 2 mailing tubes fastened parallel to each other at the proper interpupillary distance (to exclude side light). Field glasses cause too much eyestrain when used all day.

The following precautions were taken against personal bias:

1. Estimates of different observers were checked against each other whenever two or more observers were available.
2. Estimates were often checked against those of previous examinations. Color photos were not very helpful in checking estimates, since they do not show infection as well as the observer can see it.
3. Occasionally, estimates were repeated on the same tree after an interval of an hour or more.
4. To correct the observer's tendency to be unduly impressed by red foliage, percentages of unflagged as well as flagged twigs were often estimated.

Missing rings. — Increment core measurements were corrected for missing rings as follows:

1. Trees with less than 30-percent crown damage, and with no evident condition likely to affect growth seriously, were grouped by size classes (Chewiliken and Bannon) or 1921-30 ring-width classes (John Day and Belshaw). Ring patterns of most of these trees were very similar and, with the exception of the most slowly growing trees, well marked by "key" rings. The few trees with obviously dissimilar patterns were excluded, and the remaining trees were assumed to have no missing rings.

2. Average ring-width for each of the last 35 or 40 years was computed for each group. Examples are shown in figure 9. With minor exceptions at Chewiliken and Bannon, the standard ring pattern features most consistent between individual trees, as well as between groups, proved to be the peaks of growth in 1921, 1928, 1934, 1941 or 1942, and 1947, and the low points in 1924 or 1925, most of the 1930's, and 1945. Occasional trees were 1 year out of synchronization with the majority at one or two of these key points.
3. Trees whose ring pattern did not closely coincide with the standard for their group were individually graphed on transparencies, which were moved back and forth over the standard graph to determine the position of best coincidence. A high degree of coincidence with the key points was usually obtainable; otherwise, the smallest correction that gave reasonably good coincidence was assumed to be the correct one. Among the most slowly growing trees, some showed no identifiable key rings, and consequently could not be corrected, while most of the remainder had no identifiable rings except those of 1921-22 and 1941-42.

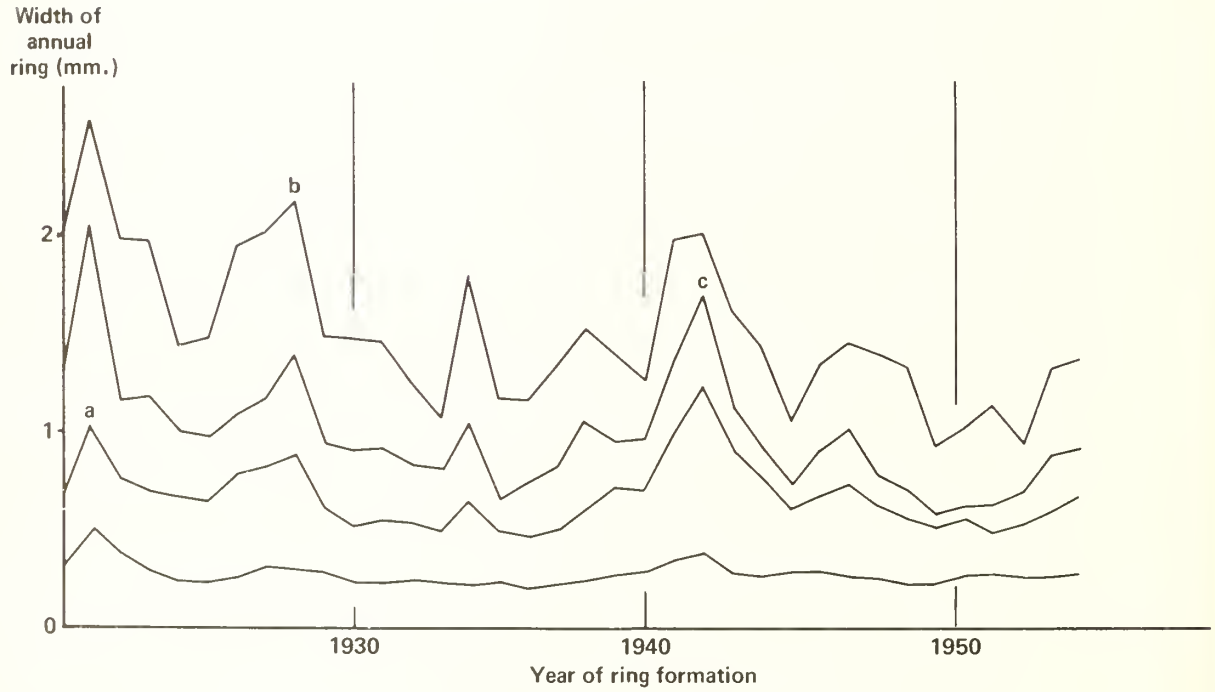

Figure 9. — Annual-ring patterns of Belshaw trees with no ring missing. Lowercase letters indicate three of the key points used in checking for missing rings. From top to bottom, lines represent seven trees with 1921-30 average ring-width more than 1.5 mm.; seven trees, rings 1.0 to 1.5 mm.; 26 trees, rings 0.5 to 1.0 mm.; and six trees, rings less than 0.5 mm.

Several of the indicated corrections seemed excessive even though the corrected patterns coincided closely with standard ones. Accordingly, cores were taken again in late 1959 from several moderately to heavily infected survivors at John Day and Belshaw. The 1955 and 1959 cores from one tree are graphed in figure 10. This tree apparently had had a good crown before Elytroderma attack, but by 1955 more than 80 percent of the crown was flagged or killed.

The 1955 core (broken line), as plotted in the graph, does not coincide with the standard at any key point except 1921 and 1928; if shifted 9 years to the left, however, it coincides not only with all key points (except, of course, the 1947 peak) but also with most of the minor irregularities in the standard pattern. The 1959 core (dotted line) by itself might have been interpreted as indicating an individual abnormality in 1925-26, one missing ring in the late 1930's, and one false ring but no missing rings after 1942; if shifted 4 years to the left, however, it coincides almost perfectly with the broken line. The two cores together indicate beyond reasonable doubt that, on the side of the trunk where the cores were taken, only four rings were formed from 1943 to 1955 and none from 1956 to 1959.

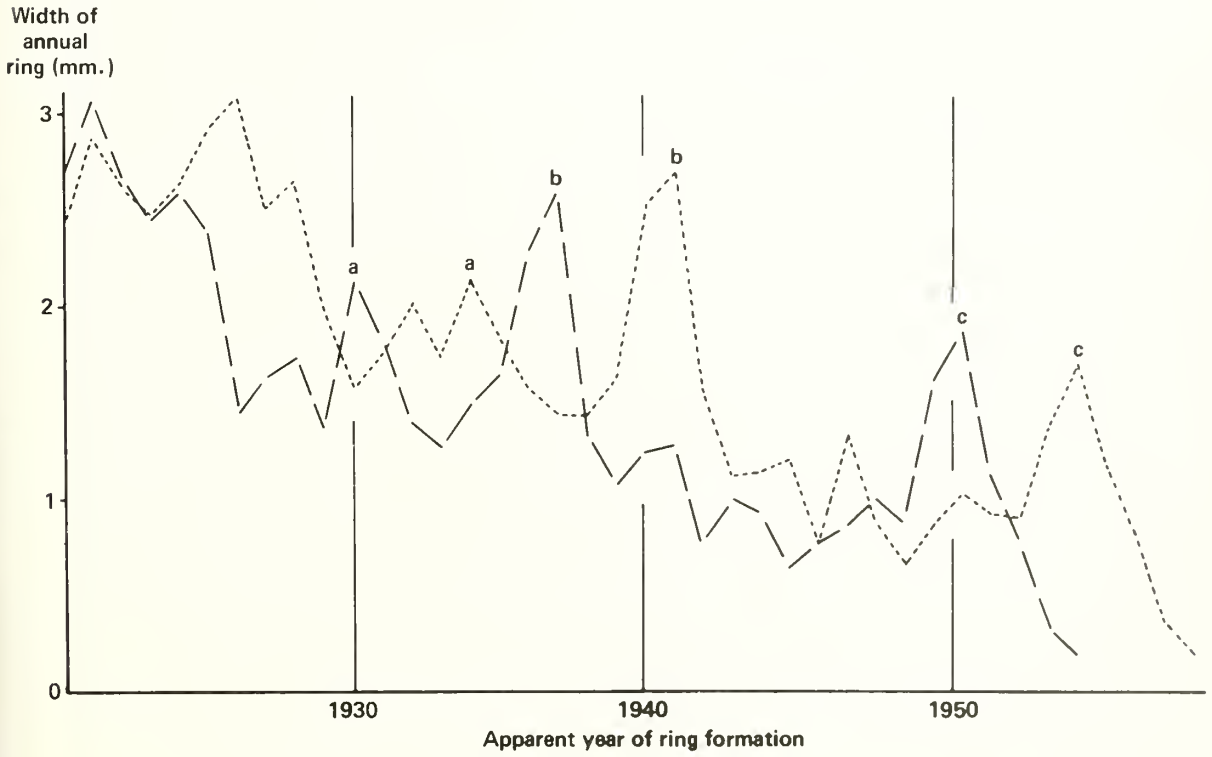

Figure 10. — Uncorrected ring patterns from heavily infected tree at Belshaw. Broken line represents increment core taken in 1955; dotted line, core taken from same tree in 1959. Lowercase letters indicate same key points as in figure 9.

As might be expected, several of the cores taken in 1959 had fewer rings missing than did the core taken from the opposite side of the same tree in 1955. When taken at a distance of only 8 inches from the 1955 core, all but two of the 1959 cores had at least as many rings missing as the 1955 core:

Plot	Trees (Number)	Average number of rings missing per tree	
		1955 core	1959 core
Belshaw	15	0	0.2
	2	1	4.5
	3	2	3.7
	2	3	5.5
	3	4	5.2
	1	5	7.0
	3	6	9.3
	3	7	10.7
	2	8	10.0
	1	9	13.0
	2	10	12.0
	2	11	12.0
John Day	10	0	.2
	3	1	2.3
	4	2	2.8
	1	3	4.0
	1	4	5.0
	2	5	6.5
	1	6	9.0
	1	7	9.0
	1	9	13.0

Some tree characteristics associated with missing rings are shown in table 13. Evenden (1940) reports two instances of trees that made no basal growth for at least 11 years after heavy defoliation by the pine butterfly.

Disease effects on Idaho plots. — Probably the most severe damage by the disease outside of Oregon has occurred on the Boise and Payette National Forests in south-central Idaho. Plots to determine rate and extent of damage to mature stands were established on the Boise National Forest in 1951 (part of one plot in 1948) by the Intermountain Forest and Range Experiment Station. These plots, like the ones in Oregon and Washington, were not established until several years after the main wave of infection had occurred.

Average crown-condition ratings on these plots are given in table 14. Mortality by crown-condition and infection classes is summarized in table 15. Heavy mortality on plot 4 was largely caused by *Fomes annosus*, common here at time of plot establishment. On some of the other plots, Elytroderma infection appeared to have aggravated damage caused by an unidentified root disease.

TABLE 13.—RADIAL GROWTH AND MISSING RINGS IN TREES KILLED BY ELYTRODERMA AND IN TREES SURVIVING

Plot and group[1]	Class		Basis	Infection		Average annual-ring width				Missing rings[4]	
	Growth[2]	Infection[3]		Average	Range	1921-30	1931-40	1946-55		Average	Range
								Average	Range		
	Mm.	*Percent*	*Number*	*--Percent--*		*----------Mm.----------*				*----Number----*	
John Day:											
Killed trees	0.5-1.0	>60	2	88	87-88	0.68	0.87	0.01	0-0.03	9.5	9-10
Survivors			3	79	76-83	.79	1.00	.20	.05-0.46	4.0	2-6
Killed trees	>1.5	30-60	2	51	43-59	1.80	1.62	.86	.69-1.04	0	0
Survivors			8	43	33-59	2.03	1.90	1.36	.26-2.20	0.2	0-2
Belshaw:											
Killed trees	<0.5	30-60	3	54	47-57	.28	.28	.03	0-0.07	8.0	6-11
Survivors			10	48	34-59	.39	.27	.15	0-0.41	4.8	0-11
Killed trees	<0.5	>60	2	68	65-71	.24	.20	.06	0-0.12	8.5	4-13
Survivors			3	71	64-77	.33	.22	.02	0-0.05	8.7	6-11
Killed trees	0.5-1.0	30-60	1	59	59	.87	.92	.07	.07	7.0	7
Survivors			11	51	31-60	.70	.61	.28	0-0.82	2.8	0-11
Killed trees	0.5-1.0	>60	1	63	63	.88	.28	0	0	12.0	12
Survivors			2	66	62-69	.75	.65	.19	0-0.37	7.0	3-11
Killed trees	1.0-1.5	>60	2	67	65-69	1.33	.73	.03	0-0.06	8.5	7-10
Survivors			2	74	70-77	1.05	.86	.08	.04-0.12	7.5	7-8
Killed trees	>1.5	>60	2	73	64-82	1.68	1.12	.15	0-0.29	5.5	0-11
Survivors			3	70	61-81	1.77	1.18	.17	.02-0.36	5.0	2-9

[1] *Killed trees are those that died after 1955 with Elytroderma at least an important contributing factor if not the principal cause of death. Survivors are those still alive when study terminated.*

[2] *Average 1921-30 ring width.*

[3] *Percentage of twigs flagged (average of all examinations before 1956).*

[4] *Since 1940.*

TABLE 14. — AVERAGE CROWN-CONDITION RATINGS OF TREES STILL ALIVE IN 1966 ON IDAHO PLOTS

Plot number[1]	Twigs flagged (average of first three annual examinations)	Trees	Average crown-condition ratings[2]	
			1951 (or 1948) examination	1966 examination
	Percent	*Number*		
2	0-40	19	2.9	2.4
	41-67	4	2.2	2.0
3	0-40	20	2.8	2.7
	41-57	1	2.0	1.0
4	0-40	10	2.8	3.0
5	0-40	19	2.9	2.8
6	0-40	15	2.4	2.0
	41-55	3	2.0	1.0

[1] *Data for plot 1 were incomplete.*

[2] *4 = excellent; 3 = good; 2 = fair; 1 = poor.*

TABLE 15. – MORTALITY[1] BY INFECTION AND CROWN-CONDITION CLASSES ON IDAHO PLOTS

Plot number[2]	Crown-condition class[3]	Total trees in infection class[4]				Trees died during study in infection class[4]			
		0-30	31-60	61-80	81-100	0-30	31-60	61-80	81-100
		Number				*Percentage*			
2	Good	12	2	0	0	0	0	--	--
	Fair	3	5	2	0	0	20	50	--
	Poor	2	0	3	2	50	--	100	100
3	Good	12	2	0	0	0	0	--	--
	Fair	6	2	0	0	0	50	--	--
	Poor	0	3	3	0	--	100	100	--
4	Good	6	1	0	0	0	100	--	--
	Fair	3	6	0	0	0	83	--	--
	Poor	2	0	0	0	100	--	--	--
5	Good	12	1	0	0	8	0	--	--
	Fair	6	1	0	0	0	0	--	--
	Poor	0	1	0	0	--	100	--	--
6	Good	3	3	0	0	0	0	--	--
	Fair	5	10	1	0	0	30	100	--
	Poor	1	2	0	2	100	100	--	100

[1] *Exclusive of trees knocked down or windthrown.*

[2] *Data for plot 1 were incomplete.*

[3] *At first examination.*

[4] *Average percentage of twigs flagged in first three annual examinations.*

Childs, T. W.

1968. Elytroderma disease of ponderosa pine in the Pacific Northwest. U. S. D. A. Forest Serv. Res. Pap. PNW-69, 46 pp., illus. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

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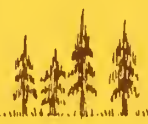
Juvenile Height Growth of Four Upper-Slope Conifers in the Washington and Northern Oregon Cascade Range



Carroll B. Williams Jr.

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PORTLAND, OREGON 1968

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RESEARCH PAPER PNW-70

JUVENILE HEIGHT GROWTH OF FOUR UPPER-SLOPE CONIFERS IN THE WASHINGTON AND NORTHERN OREGON CASCADE RANGE

by

Carroll B. Williams, Jr.

1968

PACIFIC NORTHWEST
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Portland, Oregon

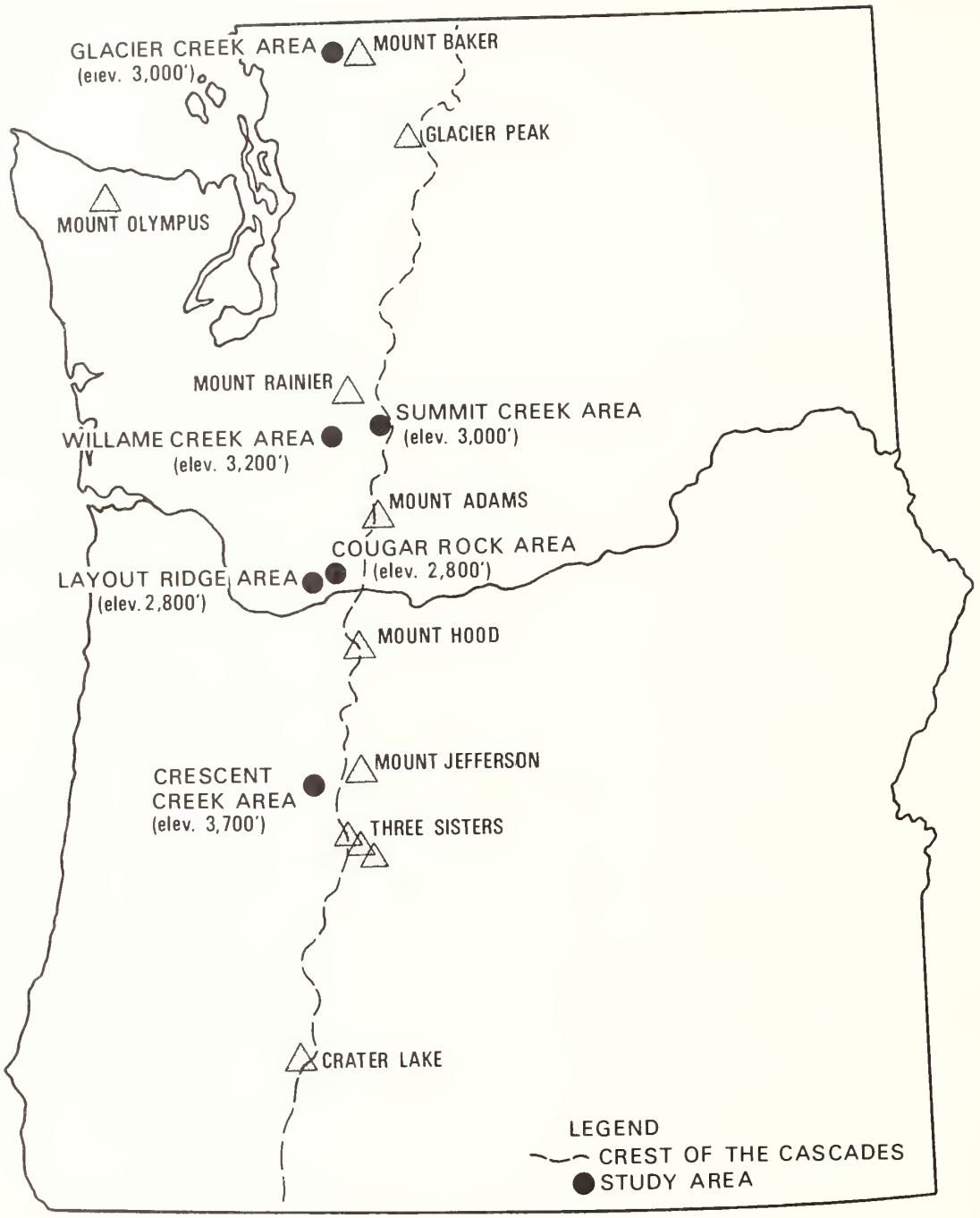

Figure 1.--Locations of the six study areas. All areas except Summit Creek had northern or northeastern aspects.

INTRODUCTION

True fir-hemlock forests cover over 3 million acres at the middle-to-high elevations--the upper slopes--of the Cascade and coastal mountain ranges of Oregon and Washington. These forests are characterized by a mixture of Pacific silver fir, *Abies amabilis* (Dougl.) Forbes; western hemlock, *Tsuga heterophylla* (Raf.) Sarg.; western white pine, *Pinus monticola* Dougl.; and mountain hemlock, *T. mertensiana* (Bong.) Carr. Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, is a common and important associate of these species, particularly below 3,500 feet. Pacific silver fir comprises over one-third of the commercial sawtimber volume in true fir-hemlock forests and western hemlock is second in abundance.

Utilization of the upper-slope forest resource is expanding because of increasing accessibility and demand for the species. Patch clearcutting is a common harvesting method, particularly in the northern part of the Cascade Range. Clearcuts, usually 40-60 acres in size, are generally slash-burned and then planted, seeded, or allowed to regenerate naturally. There are good opportunities to at least partially control composition of the new stand.

Selection of species to manage is difficult in true fir-hemlock forests because of (1) the large number of species and wide variety of habitats present, (2) lack of knowledge of growth rates of upper-slope species, and (3) the earlier low demand for several upper-slope species. Foresters often plant Douglas-fir on clearcuts. Planting success has been variable, sometimes promising at lower elevations but less successful with increasing elevation. Noble and Shasta red fir are the only true firs planted to any extent and some of these plantings have been failures. Some ponderosa pine, *Pinus ponderosa* Laws., is planted on southern exposures in central and southern Oregon.

True firs grow very slowly during their early years (Baker 1950). A series of studies on the adaptability of tree species to forest sites on Vancouver Island showed seedling Pacific silver fir had the poorest height growth of all the conifers and only fair survival (Schmidt 1959, 1960, 1961). The only juvenile growth study involving an upper-slope true fir in the Cascades was by Hanzlik (1925). At Larch Mountain in Oregon, he found noble fir took an average of 11 years to reach a height of 4.5 feet.

The present study compares the juvenile growth rates of noble fir, Pacific silver fir, Douglas-fir, and western white pine on six areas in the Washington and northern Oregon Cascade Range (fig. 1).

Figure 2.--Young Pacific silver firs usually were found growing in the shade.

METHODS

Growth was analyzed for Pacific silver fir, noble fir, western white pine, and Douglas-fir seedlings and saplings up to 4 inches diameter breast height (d.b.h.) on five clearcuts in the southern Washington and northern Oregon Cascades. The clearcuts were 15 to 20 years old at the time of the study and contained mixed natural reproduction of upper-slope species. Not all four species were present or adequately represented on all five areas; consequently, comparisons by area sometimes involved less than four species.

A Douglas-fir plantation in the Mount Baker area of northern Washington also was sampled to compare the juvenile growth of Douglas-fir and Pacific silver fir. The Douglas-fir plantation was planted at a 12- by 12-foot spacing and contained many volunteer Pacific silver fir and western hemlock seedlings and saplings--some were advance reproduction surviving the logging and burning operations, and others had seeded-in after the plantation was established. Five of the six study areas had northern to northeastern aspects. Slopes ranged from 3 to 40 percent, and elevations ranged from 2,800 to 3,700 feet. The Summit Creek area in central Washington had a southern aspect and was at an elevation of approximately 3,000 feet.

The four species were distributed differently on the study areas. Except at Glacier Creek, Pacific silver fir seedlings and saplings generally grew in groups within 100 feet of mature timber stands (fig. 2). Beyond 100 feet, they were most frequently found in the shade of other species.

Douglas-fir and noble fir reproduction was more numerous within 150-200 feet of adjacent stands than elsewhere, but also was well represented in the center of the clearcuts (fig. 3). These species sometimes grew in groups but less often than Pacific silver fir. Western white pine seedlings were sparse but well distributed throughout all study areas. Sapling-size pines were rare.

Field and Laboratory Procedure

The objective was to measure a 20-tree sample of each species on each study area, 10 to be seedlings from 6 feet tall to 2 inches d.b.h. and 10 to be saplings 2 to 4 inches d.b.h. The two size classes were used because, presumably, tree ages would span a considerable period of time and tend to average out effects, if any, of short-term weather cycles. Trees were to be free-growing with at least 5 feet of space around the crowns and without evidence of major leader injury. Number of trees was less than 20 on some areas because not enough trees met these criteria. The criterion for free-growing trees was relaxed for Pacific silver fir because of the groupwise occurrence of this species. Some study trees were the most vigorous and least crowded in a particular group but did have crowns of competitors within 5 feet.

The dominant species of arborescent and nonarborescent flora were listed for each study area, along with environmental features such as soil, aspect, humus type, and elevation (table 1).

A

Figure 3.--*A*, mixed stand of young Douglas-fir and noble fir. Density is typical of young stands within 150-200 feet of adjacent mature stands. *B*, mixed stand of young Douglas-fir, noble fir, and western white pine. Picture was taken in same stand as *A*, but more towards the center of the clearcut--approximately 300-400 feet from boundary of adjacent mature stand. Douglas-fir's juvenile growth generally exceeded that of its associates on this area.

B

Study trees were cut flush with the ground, lateral branches removed, and stems labeled as to species, tree number, and study area. Leader growth was measured to the nearest tenth of an inch. Trees were cut at Glacier Creek after the end of the 1964 growing season and from other study areas at the end of the 1963 season.

Stems were taken to the laboratory at Corvallis, Oregon, for measurement and dissection. In the laboratory, annual internodal growth was measured on each stem back to the 4.5-foot level. Stems were then sectioned at 2.0-foot height intervals and at the 4.5-foot level. Disks from these sections provided a check for the ages of the various internodes.

Stem analyses showed that all the Douglas-fir, noble fir, and western white pine study trees became established after logging, whereas only 35 of 110 Pacific silver fir trees did so. The other 75 silver firs were advance reproduction which had become established beneath the overstory of the forest and survived the logging and slash-burning operations. They had grown very slowly while under the forest canopy, but their height growth increased substantially after the overstory was logged.

Prelogging and postlogging reproduction data were kept separate for general comparisons between species, but combined when comparisons were broken down by locality. Analyses of variance were calculated with all silver fir included, then again with it excluded for better evaluation of variation among the other species.

Table 1.--Plant associations and other characteristics of six areas used to study juvenile height growth of four upper-slope conifers in Washington and Oregon

Study area	Elevation	Aspect	Forest type	Additional tree species present	Important understory vegetation (listed in order of dominance)[1]	Approximate cover	Forest humus type	Average soil depth	Soil texture
	Feet					Percent		Feet	
Summit Creek	3,000	South	Western hemlock-Pacific silver fir	Scattered western redcedar, western white pine; Douglas- and noble firs rare	*Acer circinatum, Linnea borealis, Xerophyllum tenax, Arctostaphylos nevadensis, Vaccinium ovalifolium, V. membranaceum,* and *Menziesia ferruginea*	100	Felty mor	1.4	Gravelly loam
Cougar Rock	2,800	Northeast	Pacific silver fir	Noble fir, Douglas-fir; scattered western hemlock and western white pine	*V. alaskaense, V. membranaceum, Linnea borealis, Pteridium aquilinum pubescens, Cornus canadensis*	90	Felty mor	5.0	Sandy loam
Layout Ridge	2,800	Northeast	Pacific silver fir	Noble fir, Douglas-fir; scattered western hemlock and western white pine	*V. alaskaense, V. membranaceum, V. parvifolium, A. circinatum, C. canadensis,* and *L. borealis*	100	Felty mor	4.0	Sandy loam
Crescent Creek	3,700	Northeast	Western hemlock-Douglas-fir	Noble fir, Pacific silver fir, and scattered western white pine	*Ceanothus velutinus, Rubus ursinus, Xerophyllum tenax*	100	Felty mor	4.5	Silt loam
Willame Creek	3,200	North	Western hemlock-Pacific silver fir	Douglas-fir and scattered noble fir	*L. borealis, V. alaskaense, C. canadensis, Epilobium angustifolium, A. circinatum*	100	Felty mor	3.0	Gravelly loam
Glacier Creek	3,000	North	Pacific silver fir-western hemlock	None	*P. aquilinum, R. parviflorus, R. spectabilis, V. ovalifolium, Oplopanax horridum*	100	Felty mor	--	Sandy loam

[1]Common and scientific names for trees are in accordance with Little (1953); for shrubs and herbs, Peck (1961) or Hitchcock et al. (1955-1964).

RESULTS

Some species became established more rapidly after clearcutting than others as shown by significant differences among ages of study trees. This was true even with the older Pacific silver fir reproduction excluded (table 2). Douglas-fir was the first species to become established at Summit Creek followed by western white pine and noble fir. Noble fir was first at Layout Ridge and Willame Road.

Except for Pacific silver fir generally and Douglas-fir at Summit Creek, stem analyses showed little age difference between seedlings and saplings (table 2). This finding largely eliminated the possibility of averaging out effects of any short-term climatic cycles. On the other hand, it indicated wide variation in growth rates among trees of the same species on the same cutting area, even when most trees presumably were free of competition. Analyses of variance on growth rates between seedlings and saplings, based on 1957 to 1963 internode lengths, showed that the saplings had grown significantly faster than the seedlings during this period. The saplings, then, were the most vigorous among the free-growing trees, and their growth probably approximates the best individual tree growth obtainable on the sites studied. Combined seedling and sapling data probably approximate early growth data of an intensively managed stand where trees are spaced widely enough to minimize competition.

In contrast, Pacific silver fir saplings were almost twice the age of the seedlings (table 2), requiring approximately twice the time seedlings needed to reach a height of 4.5 feet. Since the majority of Pacific silver fir seedlings and saplings were advanced reproduction, it appears that overstory canopies were denser when the saplings were established than when the younger seedlings were established.

Years required to reach 4.5 feet in height varied by species and area (table 3). Pacific silver fir took far longer than other species, but the data include the very slow-growing advanced (prelogging) reproduction. If we consider both seedlings and saplings, noble fir grew significantly slower than Douglas-fir at Willame Road and significantly slower than Douglas-fir and western white pine at Layout Ridge. There seemed to be a reversal at Summit Creek, where noble fir grew faster than Douglas-fir and western white pine on an exposed southern aspect at 3,000-foot elevation, although the difference among the species was significant only in the sapling-size class. Except for the slow-growing silver fir, all species grew about the same on the other areas.

The 1957-63 height growth differed greatly among species on each study area. With the exception of noble fir and western white pine saplings at Summit Creek, Douglas-fir outgrew all other species. Pacific silver fir always demonstrated the slowest growth. Western white pine outgrew noble fir on two areas, and noble fir was slightly better than pine on two others (table 4).

Total height-growth data from individual study areas showed no exception to Douglas-fir's superiority. However, it was not significantly different from its associate species at Layout Ridge and Crescent Creek (table 5).

Table 2.--Average age of study trees by area, size class, and species, with number of trees and significance level of difference among species

Area and size class	Tree species				Significance level[1]	
	Douglas-fir	Noble fir	Western white pine	Pacific silver fir	With no Pacific silver fir	With all Pacific silver fir
	Years					
Summit Creek:						
Seedlings	12.7	11.4	13.6	26.9	NS	**
Saplings	21.7	12.5	14.0	92.1	**	**
All	17.2	11.6	13.8	61.8	**	**
Cougar Rock:						
Seedlings	11.4	12.1	10.2	28.3	NS	**
Saplings	13.3	12.8	11.7	50.9	NS	**
All	12.4	12.5	10.7	39.6	*	**
Layout Ridge:						
Seedlings	10.7	12.7	10.8	27.4	**	**
Saplings	12.5	13.7	12.0	61.8	NS	**
All	11.6	13.2	11.0	44.6	**	**
Crescent Creek:						
Seedlings	11.0	11.8	11.1	([2])	NS	--
Saplings	12.2	12.0	11.3	--	NS	--
All	11.4	11.8	11.2	50.6	NS	**
Willame Road:						
Seedlings	10.7	11.8	--	48.7	NS	**
Saplings	11.3	12.8	--	87.6	**	**
All	11.0	12.3	--	68.2	**	**
Glacier Creek:						
Seedlings	10.5	--	--	14.3	--	**
Saplings	12.2	--	--	26.0	--	**
All	11.4	--	--	20.2	--	**

[1] * – 0.05 level of significance
** – 0.01 level of significance
NS – Nonsignificance level.

[2] No breakdown of data available for seedlings and saplings.

Table 3.--Average years study trees required to reach height of 4.5 feet, by area, size class, and species, with significance level of difference among species

Area and size class	Tree species				Significance level[1]	
	Douglas-fir	Noble fir	Western white pine	Pacific silver fir	With no Pacific silver fir	With all Pacific silver fir
	Years					
Summit Creek:						
Seedlings	7.8	7.5	10.0	22.2	NS	**
Saplings	10.0	5.5	6.9	72.7	**	**
All	8.9	7.2	8.5	49.1	NS	**
Cougar Rock:						
Seedlings	7.8	8.4	8.0	22.3	NS	**
Saplings	5.4	6.2	6.0	39.0	NS	**
All	6.6	7.3	6.7	30.7	NS	**
Layout Ridge:						
Seedlings	7.2	9.3	6.8	21.8	**	**
Saplings	5.9	6.8	5.5	48.5	NS	**
All	6.6	8.1	6.6	35.2	*	**
Crescent Creek:						
Seedlings	7.0	7.2	7.2	([2])	NS	--
Saplings	6.6	5.6	5.0	--	NS	--
All	6.9	6.7	6.7	47.6	NS	**
Willame Road:						
Seedlings	6.3	8.2	--	43.0	**	**
Saplings	5.7	6.1	--	77.4	NS	**
All	6.0	7.2	--	60.2	*	**
Glacier Creek:						
Seedlings	6.5	--	--	8.8	--	**
Saplings	5.9	--	--	17.9	--	**
All	6.2	--	--	13.3	--	**

[1] * – 0.05 level of significance
** – 0.01 level of significance
NS – Nonsignificance level.

[2] No breakdown of data available for seedlings and saplings.

Table 4.--Average internode length from 1957 to 1963, by area, size class, and species, with significance level of difference among species

Area and size class	Tree species				Significance level,[1] with all Pacific silver fir
	Douglas-fir	Noble fir	Western white pine	Pacific silver fir	
	Feet				
Summit Creek:					
Seedlings	1.19	0.97	1.03	0.78	*
Saplings	1.64	1.68	1.72	1.00	**
All	1.39	1.09	1.35	.92	**
Cougar Rock:					
Seedlings	1.04	.77	.84	.60	**
Saplings	1.74	1.35	1.42	.96	**
All	1.37	1.06	1.00	.78	**
Layout Ridge:					
Seedlings	1.15	.87	.97	.72	**
Saplings	1.88	1.47	1.48	1.10	**
All	1.51	1.17	1.05	.91	**
Crescent Creek:					
Seedlings	1.25	1.00	1.12	.79	*
Saplings	1.82	1.51	1.79	--	NS
All	1.44	1.19	1.27	1.17	NS
Willame Road:					
Seedlings	1.23	.97	--	.74	**
Saplings	2.17	1.52	--	1.16	**
All	1.67	1.25	--	.95	**
Glacier Creek:					
Seedlings	1.21	--	--	1.05	NS
Saplings	2.25	--	--	1.59	**
All	1.73	--	--	1.32	**

[1] * – 0.05 level of significance
** – 0.01 level of significance
NS – Nonsignificance level.

Table 5.--Average height of trees, by area, size class, and species, with significance level of difference among species

Area and size class	Tree species				Significance level[1]	
	Douglas-fir	Noble fir	Western white pine	Pacific silver fir	With no Pacific silver fir	With all Pacific silver fir
	Feet					
Summit Creek:						
Seedlings	10.1	8.4	8.3	8.2	NS	NS
Saplings	18.8	15.4	15.5	15.1	*	*
All	14.5	9.5	11.9	12.0	*	*
Cougar Rock:						
Seedlings	8.8	7.6	6.7	8.0	NS	NS
Saplings	16.9	13.1	12.6	14.6	**	*
All	12.9	10.4	8.7	11.3	*	NS
Layout Ridge:						
Seedlings	9.0	7.9	8.4	8.5	NS	NS
Saplings	16.9	14.5	13.6	15.3	NS	NS
All	13.0	11.2	9.3	11.9	NS	NS
Crescent Creek:						
Seedlings	10.2	9.1	9.1	([2])	NS	--
Saplings	15.4	13.6	15.0	--	NS	--
All	11.9	10.6	10.5	9.1	NS	NS
Willame Road:						
Seedlings	9.9	8.3	--	8.5	NS	NS
Saplings	17.3	14.1	--	13.9	**	**
All	13.4	11.2	--	11.2	*	**
Glacier Creek:						
Seedlings	11.2	--	--	10.5	--	NS
Saplings	19.7	--	--	17.5	--	**
All	15.4	--	--	14.0	--	**

[1] * – 0.05 level of significance
** – 0.01 level of significance
NS – Nonsignificance level.

[2] No breakdown of data available for seedlings and saplings.

Since area-species interactions are partial causes of measured differences in species growth on each area, the growth data from all areas were combined to see if the general superiority of Douglas-fir would still show significantly. The inherent superior juvenile growth ability of Douglas-fir became apparent after trees reached the 4.5-foot height (table 6). Douglas-fir grew faster than the other species during the 7 years prior to dissection of the trees, as indicated by a greater 1957-63 average internode length. Its internodal growth rate was followed by western white pine, noble fir, and Pacific silver fir, with differences among the four species significant at the 0.01 level. At the time of cutting, Douglas-fir was taller than the other species.

It was surprising that the 1957-63 growth rate of Pacific silver fir, which included a high proportion of prelogging reproduction, was surpassed by that of other species starting from seed after logging (table 6). Pacific silver firs had responded to release by the clearcutting, but not enough to compete successfully with the more vigorous species. Average total height of all silver firs did slightly exceed that of noble fir and western white pine. On the other hand, silver fir reproduction established after logging, which by ring count had about 2 years' headstart on Douglas-fir, noble fir, and western white pine, was overtaken by them.

Table 6.--Average age, dimensions, and number of study trees by species, with significance level of difference among species

Variable	Tree species					Significance level[1]	
	Douglas-fir	Noble fir	Western white pine	Pacific silver fir		With no Pacific silver fir	With all Pacific silver fir
				All trees	Postlogging trees		
Number of trees	114	87	54	110	35	--	--
Average age (years)	12.5	12.4	12.0	47.2	14.4	NS	**
Average years to reach 4.5 feet	6.9	7.3	7.3	38.6	9.0	NS	**
Average internode, 1957-63 (feet)	1.52	1.15	1.21	.99	--	**	**
Average height (feet)	13.6	10.7	10.4	11.8	10.1	**	**
Average d.b.h. (inches)	2.0	1.9	1.7	2.0	1.4	NS	*

[1] * – 0.05 level of significance
** – 0.01 level of significance
NS – Nonsignificance level.

DISCUSSION

The most interesting findings of this study were the superior juvenile growth rate of Douglas-fir relative to the true firs and western white pine and the comparatively poor juvenile growth rate of Pacific silver fir trees. But one should not conclude from this that Douglas-fir would necessarily be the best species to manage on the study areas. Evidence is accumulating that any superiority over noble fir and white pine in juvenile height growth of Douglas-fir is not maintained throughout the life cycles of these species on upper-slope sites. The author has observed that noble fir is always a component of the upper-crown canopy of essentially even-aged stands containing western hemlock and the four species studied here. Noble fir and white pine often extend above the average level of the crowns of associated species, including Douglas-fir, indicating that they maintain rapid height growth longer than their associates.

In a 400-year-old mixed stand growing on Douglas-fir site III at Larch Mountain, Douglas-fir and western hemlock diameters initially increased at a greater rate, but noble fir overtook and surpassed them between 100 and 200 years (Hanzlik 1925). In a more recent study, comparisons of height/age curves of free-growing trees in mixed stands confirmed that Douglas-fir initially grew faster than noble fir or Pacific silver fir. At 100 years, they were nearly the same height; and after about 200 years, noble fir almost always was dominant, with Douglas-fir and silver fir in codominant positions (Herman 1967).

Although the Pacific silver fir sample included prelogging reproduction and there was some crowding of study trees, it seems clear this species had slower juvenile growth characteristics than its associates. Its best growth was at Glacier Creek where it could be compared only with the Douglas-fir plantation. Douglas-fir grew significantly faster. Pacific silver fir, however, is an important species in the true fir-hemlock forests of the Pacific Northwest, accounting for over one-third of current timber volume. Seedlings are readily established under mature stands and, as on the study areas, many survive harvesting operations and become an important component of the new stand.

On upper-slope areas, Douglas-fir is more susceptible to snow damage than its associates (Williams 1966). Since only trees without evidence of major leader injury were selected for this study, little or no effect of snow damage is reflected in results. Therefore, when comparing species, one should consider that Douglas-fir reproduction may be more severely damaged by snow than the true firs or western white pine.

Number of years to reach breast height is added to increment core counts at breast height to obtain total age of standing trees. Data in table 3 may be used for this purpose but should be restricted to sites similar to study areas and where trees were free to grow during their juvenile stage. The only comparable data are Hanzlik's taken at Larch Mountain. He found it took noble fir 11 years to reach breast height compared to an average of 7.3 years in this study.

Results presented here permit comparisons of juvenile growth characteristics, but final selections of species to manage in upper-slope areas must await additional research with older age classes.

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Potential Evapotranspiration and Climate in Alaska by Thornthwaite's Classification

by
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and
Peter E. Black

Pacific Northwest Forest and Range Experiment Station
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INTRODUCTION

Long ago, Fernow (1893)[1/] wrote concerning "the desirability of utilizing the Weather Bureau, the various agricultural experiment stations, and other forces, in forming a systematic service of water statistics, and in making a careful survey of the conditions of water supplies, which may serve as a basis for the application of rational principles of water management." Over the intervening years, many of these statistics have been amassed for other States, but many still are unavailable for Alaska. This report is a step for Alaska along the path pointed out by Fernow.

Although Alaska has about 200 currently active climatological stations, it has only 0.03 rain gage per 100 square miles, or about one-tenth the gage density for conterminous United States. This density is inadequate for realistic maps of precipitation, temperature, or runoff. Nevertheless, the U.S. Weather Bureau is accumulating a large and growing record of precipitation and temperature over the State, and the U.S. Geological Survey heads an expanding stream-gaging program. There has been less attention to evaporative losses which determine differences between precipitation income and water available for human needs. As Thornthwaite (1948) pointed out, wet and dry climates are determined neither by total nor seasonal precipitation but by the relation of precipitation to the evaporative demand. For example, precipitation amounts are nearly equal in California's Mojave Desert and in Alaska's forested and frequently boggy interior. The important and often overlooked difference between climates of these regions is the amount and timing of the evaporative demand--over 100 inches yearlong on the Mojave; only about one-sixth as much during summer in Alaska's interior.

The evaporative demand usually is established at climatic stations containing evaporation pans and associated meteorological instruments requiring regular observation and service by trained personnel. Before 1963, there were only two evaporation pans in Alaska; since then, four more have been installed and others are planned. Even this severalfold expansion of evaporation measurement constitutes a minute sample in a State one-fifth the area of the 48 conterminous States. Lacking direct measurement of evaporation, one can estimate evaporative losses from weather data which have been routinely obtained at hundreds of climatic stations.

The importance of the evaporative loss is attested by the development of many formulas for estimating it from these more easily obtained climatic data. The large number of formulas also attests that none is wholly suited to its purpose. Penman's (1948) equation is accepted as best founded theoretically, but requiring sunshine, humidity, and wind data which are reported at only four climatic stations in Alaska. Papadakis (1961) fitted climate for a few Alaska stations into his worldwide classification. Thornthwaite's (1948) equation has

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[1/] Names and dates in parentheses refer to Literature Cited, p. 47.

probably been tested more widely than any other. Penman (1956) remarked that "considering it inherent simplicity and obvious limitations, the [Thornthwaite] method does surprisingly well." Because it requires only the simplest climatic data to provide reasonably reliable estimates of evapotranspiration, Thornthwaite's method was chosen for this study.

All of the previously mentioned equations provide estimates of potential evapotranspiration (PET)--water losses from fully vegetated land surfaces always abundantly supplied with soil moisture. Some equations, including Thornthwaite's, permit estimates of actual evapotranspiration (AET)--water losses from land surfaces under conditions of natural rainfall and soil moisture utilization. The concept of PET has proven especially useful since, on the basis of available heat energy, it sets a ceiling above which water losses to the atmosphere ordinarily cannot occur. PET permits hydrologists and engineers to estimate evaporative losses from lakes and rivers; agronomists and foresters to relate plant water needs to available soil moisture. Penman (1963) has described these concepts, their uses, and some of their limitations. In addition to estimates of potential and actual evapotranspiration, Thornthwaite's method provides estimates of streamflow and a quantitative method for the classification of climates.

Only a few comparisons of estimated with measured PET are known for Alaska and northwestern Canada. At Barrow, Alaska, Mather and Thornthwaite (1958) used heat balance to compute average daily PET of 1.24 millimeters as opposed to 1.20 millimeters measured from small evapotranspirometers. Close agreement was found between several estimates of PET and soil moisture loss under irrigated grass at the Alaska Agricultural Experiment Station in Palmer.[2/] Sanderson (1950) showed close agreement between PET measurements and estimates by Thornthwaite's method at Norman Wells, Northwest Territory, Canada. Brown (1965) computed annual PET of 24.75 inches at Norman Wells but measured only 19.41 inches, using some of Sanderson's equipment.

METHODS

The climates of Alaska were determined by procedures described at length by Thornthwaite (1948) and by Thornthwaite and Mather (1955). Essentially, water availability (precipitation) is compared with water need (PET). Where precipitation exceeds PET, the climate is humid. Where PET exceeds precipitation, the climate is arid. Indexes of humidity (Ih) and aridity (Ia) are expressed as percentages in the relations:

$$Ih = \frac{100(\text{precipitation})}{\text{PET}} \quad \text{and} \quad Ia = \frac{100(\text{PET}-\text{AET})}{\text{PET}}$$

[2/] Personal communication from Neil Michelson, soil physicist, Alaska Agricultural Experimental Station, Palmer, Alaska.

The humidity index has more weight than the aridity index in the moisture index (Im) calculation:

$$Im = Ih - 0.6(Ia)$$

Thornthwaite (1948) justified the coefficient 0.6 in the Im calculation by reasoning that a surplus of 6 inches of precipitation in one year counteracted a deficiency of 10 inches in another year. This assumption recognized that deep-rooted perennial plants were not totally dependent on rainfall to replenish soil moisture during the growing season but grew at reduced transpiration rates on moisture stored in the soil during previous seasons. This reasoning seems appropriate at those places in Alaska where snowmelt annually replenishes soil moisture and natural vegetation seldom shows evidence of prolonged soil moisture deficit. The influence of annually thawing permafrost on plant-water relations is not known.

Annual summaries of climatic data for Alaska (U.S. Weather Bureau 1916-66) provided most of the requisite precipitation and temperature data. Other sources included old descriptions of Alaska climate, publications by the Canada Department of Transport,[3/] Thompson,[4/] Potter,[5/] and the U.S. Weather Bureau files at Anchorage. Altogether, climatic records were obtained for 315 stations in Alaska, the coastal islands, and nearby Canada. These records varied in length from 1 year at several stations to about 100 years at Sitka. Estimates of available soil moisture were inferred from soil maps of Alaska (Kellogg and Nygard 1951) when more specific information was unavailable.

Water balances were computed manually from Thornthwaite and Mather instructions (1957) for each climatic station. Temperature and precipitation data for 207 of these stations also were processed in a computer program developed by Black (1967), which utilizes continuous functions rather than incremental tables. Figure 1, a preliminary example based on only 4 years of

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[3/] Canada Department of Transport, Meteorological Branch. Temperature normals for British Columbia. CDS #3-65, 10 pp. (Mimeogr.) 1965.

Canada Department of Transport, Meteorological Branch. Precipitation normals for British Columbia. CDS #8-65, 15 pp. (Mimeogr.) 1965.

Canada Department of Transport, Meteorological Branch. Precipitation normals for the Yukon and Northwest Territories. CDS #12-65, 7 pp. (Mimeogr.) 1965.

[4/] Thompson, H. A. Temperature normals, averages and extremes in Yukon Territory during the period 1931 to 1960. Can. Dep. Transp., Meteorol. Br., CDS #1-62, 9 pp. (Mimeogr.) 1962.

[5/] Potter, J. G. A catalogue of climatological stations in the Yukon and Northwest Territories. 21 pp. (Mimeogr.) Can. Dep. Transp., Climatol. Div., Meteorol. Br., 315 Bloor St. West, Toronto 5, Ont. 1965.

climatic data from Juneau Airport, illustrates a computer-produced table of water balance. Results by both manual and computer methods usually agreed closely; *t*-testing a random sample of 52 PET estimates showed no significant differences between results by either method. Climates were classified by applying the estimated PET in procedures described by Thornthwaite (1948).

MEAN ANNUAL WATER BALANCE

VERSION		WEATHER BUREAU STATION NO. 4100
SILVICULTURE GU-101 1966	1957 TO 1960	STREAMFLOW GAGE NO. 0
WBMEAN	LATITUDE 58N	NUMBER OF YEARS OF RECORD 4
THORNTHWAITE AND MATHER 1957		SOIL STORAGE IN MILLIMETERS 257

DATA IN MM., UNLESS SPECIFIED

COMPONENT	MONTH												
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
TDEGF	24.8	28.5	32.9	40.2	47.9	54.4	55.4	54.5	49.3	41.7	35.1	32.1	41.4
PPTIN	2.8	3.0	3.0	3.0	3.0	2.2	4.7	4.0	6.2	7.1	6.2	6.1	51.3
ARDIN	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
TDEGC	-3.9	-1.8	.5	4.6	8.8	12.5	13.0	12.5	9.6	5.4	1.7	0.0	
HEATI	0.0	0.0	0.0	.9	2.4	4.0	4.2	4.0	2.7	1.1	.2	0.0	19.5
UNPET	0	0	0	1	2	3	3	3	2	1	1	0	
CORFA	23	24	31	34	40	40	40	37	32	28	23	21	
POTET	0	0	6	39	77	103	107	94	66	37	12	0	540
PPTMM	71	77	76	77	75	57	120	101	157	180	157	155	1303
P-PET	71	77	70	38	0	-45	13	6	91	143	144	155	762
ACPWL	0	0	0			-46	0	0	0				
STRGE	328	406	257	257	256	215	228	234	257	257	257	257	
DELTA	0	0	0			-40	13	6	23	0	0	0	
ACTET	0	0	6	39	77	98	107	94	66	37	12	0	536
DEFIC	0	0	0			5	0	0	0				5
SURPL	0	0	70	38	0	0	0	0	68	143	144	155	618
WATRO	68	34	52	45	22	11	6	3	35	89	117	136	618
SNORO	0	0	15	67	33	17	8	4	2	1	1	0	148
TROMM	68	34	67	112	56	28	14	7	37	90	117	136	766
TROIN	2.7	1.3	2.6	4.4	2.2	1.1	.6	.3	1.5	3.6	4.6	5.4	30.2

Figure 1.--*Computer output, complete water balance, for Juneau Airport, Alaska.*

RESULTS

Table 1 lists, alphabetically, all of the stations for which data were available to calculate PET and to classify climate. Alaska's climate ($A\ B'_1rb'_1$; i.e. perhumid, first mesothermal,[6/] no season of rainfall deficit, temperature efficiency normal to first mesothermal) occurs in sheltered places close to the Pacific Ocean from Sitka southward. Within this region, mean annual temperature may exceed 45° F. and precipitation, usually rain, often exceeds 100 inches per year. This is Alaska's only mesothermal climate, a type sometimes compared to that of the less rainy central Atlantic States. The area, extending from Prince Rupert, British Columbia, and along the entire Pacific coast well out into the Aleutian Islands, has as much rainfall but is cooler ($A\ C'_2rc'_2$; perhumid, warm microthermal, no season of rainfall deficit, temperature efficiency normal to warm microthermal). Here, annual temperatures average nearer 40° F., similar to the less rainy climate of coastal Maine.

There are no broad expanses of humid (B) climate; apparently, the belt of humid climate is the transition between prevalent coastal and interior conditions. Thus, Skagway ($B_1C'_2sc'_2$; humid, warm microthermal, moderate summer water deficiency, temperature efficiency normal to warm microthermal) is drier than nearby coastal stations, and Nome ($B_1C'_1rc'_1$; humid, cold microthermal, little or no water deficiency, temperature efficiency normal to cold microthermal) is wetter than nearby interior stations.

The Matanuska Valley, Alaska's agricultural center, has a drier climate ($C_1C'_2dc'_2$; i.e., dry subhumid, warm microthermal, little or no water surplus, thermal efficiency normal to warm microthermal). Mean annual temperatures are about 35° F., similar to northern Wisconsin and Minnesota.

The "typical" Alaska climate ($D\ C'_2dc'_2$; i.e., semiarid, warm microthermal, little or no rainfall surplus, temperature efficiency normal to warm microthermal) centers in the upper Yukon, Copper, and Susitna River valleys. Annual precipitation consists of about 2 feet of snow and 8 or 10 inches of summer rain. Mean annual temperatures range from 20° to 25° F. and winter temperature may fall to -60° F. This climate sometimes is compared with that of the Yellowstone area in Wyoming. A similarly dry but colder climate ($D\ C'_1dc'_1$; semiarid, cold microthermal, little or no rainfall surplus, temperature efficiency normal to cold microthermal) is more widespread, extending from the Seward Peninsula eastward into Yukon Territory, from the Brooks Range southeast into British Columbia.

[6/] The terms "mesothermal," "microthermal," and "tundra," as used in this classification, express decreasing lengths and temperatures of growing seasons. The terms "cold" and "warm" have been used in conjunction with microthermal climates because they are more descriptive than the conventionally used terms "first" and "second."

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Adak*[3/]	34	51°53'	176°39'	40.2	57.9	20.94
Afognak	40	58°00'	152°47'	39.9	51.42	19.25
Aishihik*	3,170	61°39'	137°29'	24.5	9.88	21.42
Akiak*	21	60°55'	161°23'	27.3	17.55	16.54
Akulurak	40	62°30'	164°25'	27.3	14.87	15.02
Aleknagik	55	59°18'	158°54'	32.8	36.07	17.15
Alice Arm*	104	55°30'	129°30'	32.7	80.05	15.08
Allakaket*	600	66°35'	152°44'	20.5	13.78	16.97
Alpine Inn	455	61°43'	148°54'	33.4	17.36	18.49
Amchitka*	226	51°24'	179°15'E.	38.7	35.68	19.49
Anaktuvuk Pass*	2,100	68°10'	151°46'	13.2	10.68	11.34
Anchorage*	118	61°13'	149°52'	35.3	14.27	19.25
Angoon*	35	57°30'	134°35'	40.7	39.10	21.10
Aniak*	81	61°35'	159°36'	28.3	20.58	17.17
Annette*	18	55°04'	131°39'	45.6	96.59	23.70
Annex Creek*	24	58°19'	134°06'	39.8	109.11	20.91
Atka*	36	52°13'	174°12'	40.1	59.64	20.55
Atlin*	2,200	59°35'	133°39'	24.8	10.95	12.91
Attu	59	52°50'	173°11'E.	38.8	71.17	18.96
Auke Bay	35	58°24'	134°40'	41.4	58.33	17.79
Baranof*	20	57°08'	134°50'	41.5	151.68	20.98
Barrow*	22	71°18'	156°47'	9.7	4.36	7.01
Barter Island*	39	70°08'	143°38'	10.4	6.28	7.44
Bear Cove	50	59°43'	151°05'	35.3	25.74	17.47
Beaver Falls*	35	55°23'	131°28'	44.2	153.73	22.83
Bell Island*	10	55°55'	131°35'	43.6	108.67	22.24
Bering Island*	20	52°12'	165°55'E.	32.9	21.30	16.54
Bethel*	15	60°47'	161°43'	29.6	18.17	16.81
Bettles*	666	66°54'	151°31'	22.1	14.01	16.85
Big Delta*	1,268	64°08'	155°44'	27.4	11.54	18.15
Big Lake	130	61°32'	149°55'	32.8	20.9	18.06
Bonanza Mine	5,800	61°31'	142°53'	24.7	22.41	6.35
Boundary*	2,600	64°04'	141°07'	22.3	13.22	16.30
Broad Pass	2,127	63°12'	149°15'	28.3	11.4	16.69
Brooks Lake	44	58°33'	155°49'	35.4	21.18	17.29
Calder*	20	56°10'	132°27'	43.1	112.26	22.20
Candle*	24	65°56'	161°55'	20.3	9.02	14.61
Canyon Village	990	67°09'	141°05'	15.7	10.54	15.53
Cape	131	53°23'	167°54'	39.0	46.57	18.32
Cape Decision	39	56°00'	134°08'	43.7	76.49	21.73
Cape Hinchinbrook	185	60°14'	146°39'	41.6	83.30	19.07
Cape Lisburne	45	68°52'	166°08'	17.0	14.53	10.33
Cape Newenham	475	58°40'	162°10'	32.1	42.61	14.50
Cape Romanzof*	7	61°47'	166°07'	28.7	27.14	14.80

NOTE: See footnotes at end of table.

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\ (P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index $Mi=Ih-0.6Ia$	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
20.91	36.97	176.6	0.03	0.1	+176	70	$AC'_2rc'_2$
19.19	32.17	167.1	0.06	0.3	+167	72	$AC'_2rc'_2$
9.88	--	--	11.54	53.9	- 32	69	$DC'_2dc'_2$
14.94	1.01	6.1	1.60	9.7	+ 0.3	77	$C_2C'_1dc'_1$
12.97	--	--	2.05	13.6	- 8	80	$C_1C'_2dc'_1$
16.80	18.92	110.3	0.35	2.0	+109	76	$AC'_2rc'_2$
15.04	64.97	430.8	0.04	0.3	+431	79	$AC'_1rc'_1$
13.31	--	--	3.66	21.6	- 13	76	$C_1C'_2dc'_2$
15.28	--	--	3.21	17.4	- 10.4	74	$C_1C'_2dc'_2$
19.37	16.19	83.1	0.12	0.6	+ 83	72	$B_4C'_2rc'_2$
8.82	--	--	2.52	22.2	- 13	88	$C_1C'_1dc'_1$
15.20	--	--	4.05	21.0	- 13	72	$C_1C'_2dc'_2$
20.51	18.00	85.3	0.59	2.8	+ 84	72	$B_4C'_2rc'_2$
15.28	3.41	19.9	1.89	11.0	+ 13	76	$C_2C'_2rc'_2$
23.70	72.89	307.6	0	0	+308	66	$AB'_1rb'_1$
20.91	88.20	421.8	0	0	+422	70	$AC'_2rc'_2$
20.55	39.09	190.2	0	0	+190	71	$AC'_2rc'_2$
8.31	--	--	4.60	35.6	- 21	84	$DC'_1dc'_1$
18.96	52.21	275.4	0	0	+275	73	$AC'_2rc'_2$
17.79	40.54	227.9	0	0	+228	75	$AC'_2rc'_2$
20.98	130.70	623.0	0	0	+623	70	$AC'_2rc'_2$
4.36	--	--	2.65	37.8	- 23	102	$DD'dd'$
6.28	--	--	1.16	15.6	- 9	100	$C_1D'dd'$
13.83	8.27	47.3	3.64	20.8	+ 45	75	$B_2C'_2sc'_2$
22.83	130.90	573.4	0	0	+573	68	$AB'_1rc'_2$
22.24	86.43	388.6	0	0	+389	68	$AC'_2rc'_2$
15.05	4.76	28.8	1.49	9.0	+ 23	77	$B_1C'_1rc'_1$
14.05	1.36	8.1	2.76	16.4	- 2	77	$C_1C'_1dc'_1$
13.11	--	--	3.74	22.2	- 13	76	$C_1C'_2dc'_2$
11.54	--	--	6.61	36.4	- 22	74	$DC'_2dc'_2$
15.07	2.84	15.7	2.99	16.6	+ 6.0	74	$C_2C'_2rc'_2$
6.21	16.06	252.9	0.14	2.2	+251	104	$AD'rd'$
13.23	--	--	3.07	18.9	- 11	77	$C_1C'_1dc'_1$
10.89	--	--	5.80	34.8	- 21	78	$DC'_1dc'_1$
15.78	3.89	22.5	1.51	8.7	+ 17	77	$C_2C'_2rc'_1$
22.17	90.06	405.7	0.03	0.1	+405	68	$AC'_2rc'_2$
8.74	--	--	5.87	40.2	- 24	80	$DC'_1dc'_1$
10.54	--	--	4.99	32.1	- 19	79	$C_1C'_1dc'_1$
18.32	28.25	154.4	0	0	+154	76	$AC'_2rc'_2$
21.73	54.76	252.0	0	0	+252	69	$AC'_2rc'_2$
19.07	64.23	336.8	0	0	+337	73	$AC'_2rc'_2$
9.65	4.20	40.7	0.68	6.6	+ 37	90	$B_1D'rd'$
14.50	28.11	193.9	0	0	+194	83	$AC'_1rc'_1$
14.29	12.34	83.4	0.51	3.4	+ 81	80	$B_4C'_1rc'_1$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Cape Sarichef*[3/]	175	54°33'	164°56'	38.0	74.25	18.07
Cape Spencer*	81	58°12'	136°38'	42.2	68.77	21.85
Cape St. Elias*	50	59°48'	144°36'	43.2	68.35	22.17
Cape Thompson*	33	68°06'	165°46'	18.9	14.21	11.85
Carmacks*	1,710	62°06'	136°18'	25.2	8.73	17.91
Caswell*	290	61°58'	150°01'	31.0	25.06	18.66
Central*	870	65°32'	144°48'	20.0	10.34	18.54
Chalkyitsik	560	66°38'	143°43'	17.0	5.30	15.55
Chena Hot Springs	1,574	65°03'	146°04'	20.9	11.14	15.89
Chernofski Harbor*	25	53°26'	167°21'	40.2	52.75	20.16
Chichagof*	10	57°40'	136°05'	41.9	122.91	21.38
Chickaloon*	929	61°48'	148°27'	32.7	14.00	18.11
Chicken	1,360	64°04'	141°56'	19.3	8.62	17.01
Chignik	10	56°18'	158°23'	37.0	158.1	16.63
Chistochina	2,000	62°34'	144°45'	26.2	12.4	18.85
Chitina*	580	61°32'	144°27'	28.3	12.81	18.39
Circle City	700	65°48'	144°04'	21.2	10.3	17.23
Circle Hot Springs*	1,000	65°29'	144°34'	22.2	10.20	17.80
Clear Airport	546	64°18'	149°09'	21.1	13.91	17.38
Clear Water	1,100	64°03'	145°31'	15.9	14.43	17.69
Coal Harbor*	30	55°24'	160°49'	39.1	48.51	18.82
Cold Bay*	93	55°12'	162°43'	38.4	33.20	17.81
Colleen River	1,120	67°45'	142°34'	14.7	11.15	13.19
Cooper Lake Project	350	60°22'	149°40'	37.3	30.79	19.14
Copper Center*	1,031	61°58'	145°19'	26.1	9.15	17.40
Copper Valley School	1,030	62°05'	145°18'	26.8	10.53	18.31
Cordova*	25	60°32'	145°45'	38.6	98.64	19.13
Council*	95	64°53'	163°41'	26.5	13.96	15.47
Craig*	13	55°29'	133°09'	44.9	106.26	23.46
Crooked Creek*	125	61°52'	158°15'	29.0	14.09	17.60
Curry*	516	62°37'	150°02'	34.9	43.67	18.94
Dahl	250	65°22'	164°41'	17.4	6.86	13.43
Davis River	22	55°46'	130°11'	39.9	100.6	19.40
Dawson*	1,062	64°04'	139°26'	23.6	12.67	18.11
Dease Lake*	2,678	58°25'	130°00'	19.6	15.25	10.20
Devil's Club	360	60°58'	149°11'	37.8	39.82	19.65
Dillingham*	50	59°03'	158°27'	33.4	25.03	17.95
Dutch Harbor*	13	53°53'	166°32'	40.7	61.64	20.59
Eagle*	821	64°45'	141°12'	25.1	11.24	17.67
Eielson Field*	547	64°39'	147°04'	25.1	13.99	18.39
Eklutna Lake*	882	61°24'	149°09'	30.7	12.38	16.93
Eklutna Project*	38	61°28'	149°10'	33.7	18.34	19.25
Eldred Rock*	55	58°58'	135°13'	41.9	51.21	21.50
Elmendorf*	192	61°14'	149°52'	34.8	15.73	19.65

NOTE: See footnotes at end of table.

Actual evapo-transpiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\,(P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
17.83	56.18	310.9	0.24	1.3	+310	74	$AC'_2rc'_2$
21.85	46.92	214.7	0	0	+215	69	$AC'_2rc'_2$
22.17	46.18	208.3	0	0	+208	68	$AC'_2rc'_2$
10.67	2.36	19.9	1.18	10.0	+ 14	86	$C_2C'_1rc'_1$
8.62	--	--	9.29	51.9	- 31	75	$DC'_2dc'_2$
16.57	6.40	34.3	2.09	11.2	+ 27	73	$B_1C'_2rc'_2$
10.20	--	--	8.34	45.0	- 27	74	$DC'_2dc'_2$
5.30	--	--	10.25	65.9	- 39.5	79	$DC'_1dc'_1$
11.14	--	--	4.75	29.9	- 18	78	$DC'_1dc'_1$
20.04	32.59	161.7	0.12	0.6	+161	71	$AC'_2rc'_2$
21.38	101.53	474.9	0	0	+475	69	$AC'_2rc'_2$
12.68	--	--	5.43	30.0	- 18	74	$C_1C'_2dc'_2$
8.62	--	--	8.39	49.3	- 30	76	$DC'_2dc'_2$
16.63	141.47	850.7	0	0	+851	77	$AC'_1rc'_1$
12.30	--	--	6.55	34.7	- 21	73	$DC'_2dc'_2$
11.81	--	--	6.58	35.8	- 21	74	$DC'_2dc'_2$
10.15	--	--	7.08	41.1	- 25	76	$DC'_2dc'_2$
10.20	--	--	7.60	42.7	- 26	75	$DC'_2dc'_2$
12.37	--	--	5.01	28.8	- 17	75	$C_1C'_2dc'_2$
14.43	--	--	3.26	18.4	- 11	75	$C_1C'_2dc'_2$
18.80	29.69	157.8	0.02	0.1	+158	73	$AC'_2rc'_2$
17.52	15.39	86.4	0.29	1.6	+ 85	75	$B_4C'_2rc'_2$
11.15	--	--	2.04	15.5	- 6	83	$C_1C'_1dc'_1$
15.71	11.65	60.9	3.43	17.9	+ 51	73	$B_2C'_2rc'_2$
9.15	--	--	8.25	47.4	- 28	75	$DC'_2dc'_2$
10.53	--	--	7.78	42.5	- 26	74	$DC'_2dc'_2$
19.13	79.51	415.6	0	0	+416	73	$AC'_2rc'_2$
11.69	--	--	3.78	24.4	- 15	79	$C_1C'_1dc'_1$
23.46	82.80	352.9	0	0	+353	67	$AB'_1rb'_1$
14.09	--	--	3.51	19.9	- 12	75	$C_1C'_2dc_2$
18.62	24.73	130.6	0.32	1.7	+130	73	$AC'_2rc'_2$
6.86	--	--	6.57	48.9	- 29	83	$DC'_1dc'_1$
19.40	81.20	418.6	0	0	+419	72	$AC'_2rc'_2$
12.48	--	--	5.63	31.1	- 19	74	$C_1C'_2dc'_2$
9.65	5.05	49.5	0.55	5.4	+ 46	91	$B_2D'rd'$
18.34	20.17	102.6	1.31	6.7	+ 98	72	$B4C'_2rc'_2$
16.53	7.08	39.4	1.42	7.9	+ 35	74	$B_1C'_2rc'_2$
19.92	41.05	199.4	0.67	3.3	+197	71	$AC'_2rc'_2$
10.41	--	--	7.26	41.1	- 25	75	$DC'_2dc'_2$
13.99	--	--	4.40	23.9	- 14	74	$C_1C'_2dc'_2$
12.32	--	--	4.61	27.2	- 16	76	$C_1C'_1dc'_2$
15.16	--	--	4.09	21.2	- 13	72	$C_1C'_2dc'_2$
20.47	29.71	138.2	1.03	4.8	+135	69	$AC'_2rc'_2$
15.31	--	--	4.34	22.1	- 13	72	$C_1C'_2dc'_2$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Eureka	3,326	61°57'	147°10'	24.0	17.09	12.33
Fairbanks*[3/]	436	64°49'	147°52'	26.2	11.92	18.35
False Pass	20	54°50'	163°40'	39.6	80.7	17.58
Farewell*	20	62°30'	153°54'	25.7	16.25	16.42
Five Finger Light*	70	57°16'	133°37'	43.4	57.84	22.48
Flat*	326	62°29'	158°05'	27.5	18.23	17.32
Fort Egbert	573	64°46'	141°12'	21.3	10.3	16.95
Fort Gibbon	235	65°12'	152°00'	23.3	10.7	16.91
Fort Liscom*	9	61°06'	146°27'	25.1	74.4	18.15
Fort Tongass*	20	54°45'	130°35'	47.8	133.8	24.92
Fort Yukon*	419	66°35'	145°18'	20.7	6.53	17.91
Fortmann*	132	55°36'	131°25'	45.2	144.40	21.93
Galena*	120	64°43'	156°54'	25.2	14.62	17.83
Gambell*	25	63°46'	171°48'	24.2	15.83	11.30
Geese Islands	15	56°43'	153°55'	41.9	57.4	21.76
Girdwood	50	60°56'	149°10'	35.9	38.4	19.27
Glennallen	1,456	62°07'	145°32'	22.9	8.21	15.57
Golovin	12	64°33'	163°01'	26.6	9.02	14.97
Goodnews Bay	20	59°10'	162°30'	31.4	25.3	15.60
Guard Island*	20	55°27'	131°53'	46.0	65.43	23.90
Gulkana*	1,572	62°17'	145°27'	26.9	11.70	17.44
Gull Cove*	18	58°12'	136°09'	41.6	102.84	21.02
Gustavus*	22	58°25'	135°42'	40.9	54.86	20.87
Haines*	100	59°14'	135°26'	40.3	60.64	20.79
Haines Junction*	1,960	60°46'	137°35'	26.5	10.94	16.57
Herschel Island*	15	69°35'	139°15'	10.7	5.91	9.06
High Lake Lodge	2,760	62°54'	149°05'	27.1	24.5	14.18
Hollis*	15	55°28'	132°40'	44.2	103.58	22.83
Holy Cross*	150	62°10'	159°45'	29.2	18.35	17.40
Homer*	67	59°38'	151°30'	37.3	25.25	18.86
Hooper Bay	35	61°32'	166°05'	30.0	17.07	15.24
Hughes*	545	66°04'	154°20'	23.6	13.91	17.56
Hyder*	9	55°55'	130°01'	40.9	89.58	21.30
Igloo	4	65°12'	165°04'	21.8	9.06	13.85
Iliamna*	145	59°44'	154°57'	33.7	25.78	17.80
Indian River	735	62°45'	149°50'	31.1	36.7	16.97
Iniskin*	300	59°45'	153°14'	33.9	78.23	17.36
Intricate Bay	170	59°43'	154°28'	33.7	35.05	16.62
Jualin	710	58°49'	135°02'	42.8	81.96	21.28
Juneau*	72	58°18'	134°24'	42.5	90.25	21.89
Juneau Airport*	12	58°22'	134°35'	40.5	54.62	20.63
Kake*	8	56°59'	133°55'	42.7	54.51	21.89
Kalsin Bay	20	57°34'	152°27'	39.7	100.3	17.91
Kalskag	90	61°27'	160°49'	28.6	12.8	18.07

NOTE: See footnotes at end of table.

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\ (P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index $MI = Ih - 0.6Ia$	Summer need	Climatic type[27]
Inches	Inches		Inches			Percent	
12.18	4.76	38.6	0.15	1.2	+ 38	85	$B_1C'_1rc'_1$
10.94	--	--	7.41	40.4	- 24	74	$DC'_2dc'_2$
17.58	63.12	359.0	0	0	+359	75	$AC'_2rc'_2$
15.68	--	--	0.74	4.5	- 3	77	$C_1C'_1dc'_1$
22.28	35.36	157.3	0	0	+157	68	$AC'_2rc'_2$
13.81	0.91	5.3	3.51	20.3	- 7	75	$C_1C'_2dc'_2$
10.32	--	--	6.63	39.1	- 23	76	$DC'_2dc'_2$
10.70	--	--	6.21	36.7	- 22	76	$DC'_2dc'_2$
17.91	56.25	309.9	0.24	1.3	+309	74	$AC'_2rc'_2$
24.92	108.88	436.9	0	0	+437	65	$AB'_1rb'_1$
6.53	--	--	11.38	63.5	- 38	75	$DC'_2dc'_2$
21.93	122.47	558.5	0	0	+559	69	$AC'_2rc'_2$
14.62	--	--	3.21	18.0	- 11	75	$C_1C'_2dc'_2$
10.36	4.53	40.1	0.94	8.3	+ 35	88	$B_1C'_1rd'$
21.76	35.64	163.8	0	0	+164	69	$AC'_2rc'_2$
16.63	19.13	99.3	2.64	13.7	+ 91	72	$B_4C'_2rc'_2$
8.21	--	--	7.36	47.3	- 28	79	$DC'_1dc'_1$
9.02	--	--	5.95	39.7	- 24	80	$DC'_1dc'_1$
14.17	9.70	62.2	1.43	9.2	+ 57	78	$B_2C'_1rc'_1$
23.90	41.53	173.8	0	0	+174	66	$AB'_1rb'_1$
11.54	--	--	5.90	33.8	- 20.3	75	$DC'_2dc'_2$
21.00	81.82	389.2	0.02	0.1	+389	70	$AC'_2rc'_2$
20.67	33.99	162.9	0.20	1.0	+163	70	$AC'_2rc'_2$
18.58	39.85	191.7	2.21	10.6	+185	70	$AC'_2rc'_2$
10.94	--	--	5.63	34.0	- 20.4	77	$DC'_1dc'_1$
5.83	--	--	3.23	35.7	- 21	94	DD'dd'
13.92	10.32	72.8	0.26	1.8	+ 71	81	$B_3C'_1rc'_1$
22.71	80.75	353.7	0.12	0.5	+353	68	$AB'_1rc'_2$
14.64	0.95	5.5	2.76	15.9	- 4	75	$C_1C'_2dc'_2$
16.65	6.39	33.9	2.21	11.7	+ 27	73	$B_1C'_2rc'_2$
13.91	1.83	12.0	1.33	8.7	+ 7	79	$C_2C'_1rc'_1$
13.43	--	--	4.13	23.5	- 14	75	$C_1C'_2dc'_2$
21.06	68.28	320.6	0.24	1.12	+320	70	$AC'_2rc'_2$
8.80	--	--	5.05	36.5	- 22	82	$DC'_1dc'_1$
16.38	7.98	44.8	1.42	8.0	+ 40	75	$B_2C'_2rc'_2$
14.88	19.73	116.3	2.09	12.3	+109	76	$AC'_2rc'_2$
17.36	60.87	350.6	0	0	+351	75	$AC'_2rc'_2$
16.30	18.43	110.9	0.32	1.9	+109.8	77	$AC'_1rc'_1$
21.05	60.68	285.2	0.23	1.1	+284	70	$AC'_2rc'_2$
21.89	68.36	312.2	0	0	+312	69	$AC'_2rc'_2$
20.53	33.99	164.8	0.10	0.5	+165	70	$AC'_2rc'_2$
21.38	32.62	149.0	0.51	2.4	+148	69	$AC'_2rc'_2$
17.91	82.39	460.0	0	0	+460	75	$AC'_2rc'_2$
12.80	--	--	5.27	29.2	- 16	74	$C_1C'_2dc'_2$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Kanatak	23	57°34'	156°02'	42.1	57.83	20.84
Kasilof*[3/]	80	60°23'	151°17'	34.8	17.10	18.82
Katalla	10	60°12'	144°33'	41.3	110.6	19.05
Kenai*	85	60°34'	151°16'	33.3	18.42	17.17
Kennecott*	2,210	61°29'	142°53'	30.2	23.47	16.57
Kenney Lake	1,200	61°44'	144°43'	26.6	16.95	15.07
Kensington Mine	2,025	58°52'	135°08'	40.0	74.65	19.40
Kechumstuk	2,600	64°07'	142°20'	18.1	13.4	14.22
Ketchikan*	15	55°21	131°39'	46.1	151.19	23.74
Killisnoo*	20	57°22'	134°29'	40.7	52.9	20.67
Kinsham Cove	13	57°41'	136°06'	44.8	117.0	22.14
King Island	100	64°56'	168°01'	29.2	12.53	14.08
King Salmon*	44	58°41'	157°05'	34.1	22.46	17.87
Kitimat*	55	54°00'	128°42'	37.8	96.78	18.90
Kitoi Bay*	20	58°11'	152°21'	39.1	62.62	16.57
Kiukpalik Island	20	58°36'	153°34'	38.8	75.7	17.47
Klatt's Farm	150	61°04'	149°54'	33.8	16.53	18.96
Klukwan*	91	59°24'	135°54	35.7	21.16	19.80
Kobuk	140	66°54'	156°52'	19.4	20.7	14.30
Kodiak*	152	57°48'	152°24'	40.5	61.54	19.96
Kokhanok Bay*	115	59°30'	154°52'	33.0	31.33	16.18
Komakuk Beach	30	69°35'	140°11'	10.9	6.06	9.80
Kotzebue*	10	66°52'	162°38'	20.6	8.02	13.39
Ladd Air Force Base*	464	64°50'	147°36'	26.7	12.60	18.70
Lake Chandalar	1,900	67°30'	148°30'	14.2	12.01	13.25
Lake Minchumina*	693	63°53'	152°17'	25.3	11.99	17.87
Lake Nerka*	65	59°34'	159°02'	31.1	57.85	17.44
Larsen Bay*	15	57°32'	154°05'	39.4	21.90	20.27
Latouche*	45	60°03'	147°54'	41.5	180.96	20.67
Lazy Bay	12	56°53'	154°15'	40.3	45.41	19.31
Lignite	1,176	63°57'	148°59'	27.0	16.0	15.85
Lincoln Rock*	25	56°03'	132°46'	44.9	60.31	23.39
Linger Longer	700	59°26'	136°17'	37.7	36.63	19.10
Little Diomede	150	65°45'	168°56'	22.1	28.71	10.60
Little Port Walter*	14	56°23'	134°39'	43.2	222.47	22.32
Livengood*	730	65°30'	148°29'	24.8	12.75	17.95
Mankomen Lake	3,330	62°59'	144°29'	24.3	26.0	14.59
Manley Hot Springs*	265	65°00'	150°39'	25.1	15.19	17.80
Matanuska Expt. Station*	150	61°34'	149°16'	35.5	15.40	19.76
May Creek	1,500	62°21'	142°41'	26.1	13.90	15.01
Mayo Landing*	1,625	63°36'	135°53'	14.3	11.16	11.89
McGrath*	334	62°58'	155°37'	25.2	19.13	17.68
McKinley Park*	2,092	63°42'	149°00'	27.5	14.44	14.61
Meier	2,717	62°47'	145°27'	22.4	15.27	13.35

NOTE: See footnotes at end of table.

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100(P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
20.78	36.99	177.5	0.06	0.3	+177	70	$AC'_2rc'_2$
15.24	--	--	3.58	19.0	- 11	73	$C_1C'_2dc'_2$
19.05	91.55	480.6	0	0	+481	73	$AC'_2rc'_2$
15.12	1.25	7.3	2.05	11.9	+ 0.2	76	$C_2C'_2rc'_2$
15.00	6.90	41.6	1.57	9.5	+ 36	77	$B_1C'_1rc'_1$
10.78	1.88	12.5	4.29	28.5	- 4.6	79	$C_1C'_1dc_1$
19.14	55.25	284.8	0.26	1.3	+284	72	$AC'_2rc'_2$
11.75	--	--	2.47	17.4	- 10.4	81	$C_1C'_1dc'_1$
23.74	127.45	536.9	0	0	+537	66	$AB'_1rb'_1$
20.31	32.23	155.9	0.36	1.74	+155	70	$AC'_2rc'_2$
22.14	94.86	428.5	0	0	+429	68	$AC'_2rc'_2$
10.45	--	--	3.63	25.8	- 15	81	$C_1C'_1dc'_1$
15.98	4.59	25.7	1.89	10.6	+ 19	75	$C_2C'_2rc'_2$
18.90	77.88	412.1	0	0	+412	73	$AC'_2rc'_2$
16.57	45.05	271.9	0	0	+272	77	$AC'_1rc'_1$
17.47	58.23	333.3	0	0	+333	75	$AC'_2rc'_2$
15.45	--	--	3.51	18.5	- 11	73	$C_1C'_2dc'_2$
15.17	1.36	6.9	4.63	23.4	- 7	72	$C_1C'_2dc'_2$
12.13	6.40	44.8	2.17	15.2	+ 36	81	$B_1C'_1rc'_1$
19.92	41.58	209.3	0.04	0.2	+209	71	$AC'_2rc'_2$
15.57	15.15	93.6	0.61	3.8	+ 91	77	$B_4C'_1rc'_1$
5.90	--	--	3.90	39.8	- 24	92	DD'dd'
8.02	--	--	5.37	40.1	- 24	83	$DC'_1dc'_1$
12.60	--	--	6.10	32.6	- 19.6	72	$C_1C'_2dc'_2$
10.73	--	--	2.52	19.0	- 11	83	$C_1C'_1dc'_1$
11.99	--	--	5.88	32.9	- 19.7	75	$C_1C'_2dc'_2$
17.44	40.41	231.7	0	0	+232	75	$AC'_2rc'_2$
16.18	1.63	8.0	4.09	20.2	- 4	71	$C_1C'_2dc'_2$
20.67	160.29	775.5	0	0	+776	70	$AC'_2rc'_2$
19.04	26.10	135.2	.27	1.4	+134	72	$AC'_2rc'_2$
14.29	0.15	1.0	1.56	9.8	- 4.9	78	$C_1C'_1dc'_1$
23.36	36.92	157.8	0.03	0.1	+158	67	$AB'_1rc'_2$
14.99	17.53	91.8	4.11	21.5	+ 79	73	$B_3C'_2sc'_2$
9.41	18.11	170.8	1.19	11.2	+164	90	AD'rd'
22.32	200.15	896.7	0	0	+897	68	$AC'_2rc'_2$
12.72	--	--	5.23	29.1	- 17	74	$C_1C'_1dc'_2$
14.57	11.41	78.2	0.02	0.1	+ 78	80	$B_3C'_1rc'_1$
14.80	--	--	3.00	16.9	- 10.1	75	$C_1C'_1dc'_2$
15.40	--	--	4.36	22.1	- 13	72	$C_1C'_2dc'_2$
11.86	--	--	3.15	21.0	- 13	80	$C_1C'_1dc'_1$
9.09	--	--	2.80	23.5	- 14	86	$C_1D'dc'_1$
15.54	1.45	8.2	2.14	12.1	+ 1	75	$C_2C'_1rc'_2$
13.58	--	--	3.03	18.2	- 11	77	$C_1C'_1dc'_1$
12.83	1.92	14.4	0.52	3.9	+ 10.4	83	$C_2C'_1rc'_1$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Mendenhall*[3/]	85	58°24'	134°32'	40.0	93.73	20.71
Middleton Island*	39	59°28'	146°19'	42.1	61.01	21.93
Mile 28, Haines H'way	400	50°24'	135°54'	35.5	31.79	19.76
Moose Pass	480	60°28'	149°23'	33.5	43.66	17.39
Moose Run	395	61°15'	149°40'	33.0	19.2	17.43
Moose Valley*	400	59°25'	136°03'	35.8	33.15	19.65
Moses Point*	15	64°43'	162°04'	25.0	20.50	15.71
Mountain Village*	39	62°07'	163°45'	27.7	16.26	16.18
Naknek*	49	58°45'	157°05'	34.4	22.89	18.66
Nenana*	356	64°33'	149°05'	25.8	11.13	18.11
New Hazelton*	1,150	55°14'	127°36'	29.3	19.17	14.06
Nikolski	18	52°27'	168°52'	38.0	32.81	16.62
Ninilchik	25	60°05	151°40'	34.3	25.54	16.33
Nome*	13	64°30'	165°26'	26.3	18.96	15.00
Noorvik*	68	66°50'	161°00'	22.1	16.40	12.01
North Dutch Island*	33	60°46'	147°48'	41.0	126.84	20.20
Northeast Cape*	38	63°17'	168°41'	25.1	18.24	12.05
North Fork	2,700	64°30'	142°10'	19.9	12.6	16.00
Northway*	1,713	63°00'	141°50'	22.4	11.34	17.52
Nulato*	210	64°43'	158°04'	25.9	15.60	16.26
Nunivak*	40	60°23'	166°12'	29.6	14.65	15.28
Nyac*	450	61°00'	159°59'	30.4	22.65	17.01
Ohogamiut	45	61°38'	161°54'	33.3	23.65	21.54
Old Crow*	800	67°35'	139°50'	13.3	7.54	13.74
Ophir	400	63°10'	156°33'	19.9	12.6	16.00
Palmer*	220	61°37'	149°06'	35.6	16.61	19.72
Passage Canal	12	60°47'	148°13'	39.8	190.19	19.18
Paxson*	2,697	63°03'	145°27'	24.3	19.65	14.53
Perseverence Camp	1,100	58°18'	134°20'	37.7	160.1	18.85
Petersburg*	50	56°49'	132°57'	42.3	105.01	21.69
Pilgrim Springs*	50	65°05'	164°58'	24.1	5.86	15.71
Pilot Point	50	57°37'	157°34'	37.4	19.8	18.25
Pilot Station*	50	61°58'	163°00'	28.4	16.61	16.18
Platinum*	20	59°01'	161°47'	32.2	18.75	16.93
Point Hope*	13	68°20'	166°48'	18.7	10.21	10.87
Point Lay*	10	69°45'	163°03'	13.3	6.91	10.75
Point Retreat*	20	58°25'	134°57'	42.2	78.68	21.38
Porcupine Creek*	1,800	59°22'	136°16'	34.5	39.00	19.13
Port Alexander*	18	56°10'	134°45'	43.8	169.10	22.80
Port Alsworth	230	60°12'	154°18'	32.8	21.32	16.72
Port Heiden	92	56°57'	158°37'	36.1	17.11	16.76
Port Moller*	18	55°56'	160°30'	38.1	19.2	18.94
Portage*	35	60°51'	148°59'	36.5	57.13	19.29
Prince Rupert*	170	54°17'	130°23'	40.0	94.41	20.24

NOTE: See footnotes at end of table.

Actual evapo-transpiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\ (P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
20.71	73.02	352.6	0	0	+353	70	$AC'_2rc'_2$
21.77	39.08	178.2	0.16	0.7	+178	69	$AC'_2rc'_2$
15.39	12.03	60.9	4.37	22.1	+ 48	72	$B_2C'_2sc'_2$
13.63	26.27	151.1	3.76	21.6	+138	75	$AC'_2rc'_2$
14.00	1.77	10.2	3.43	19.67	- 2	75	$C_1C'_2sc'_2$
15.79	13.50	68.7	3.86	19.64	+ 57	72	$B_2C'_2sc'_2$
14.50	4.79	30.5	1.21	7.7	+ 25	78	$B_1C'_1sc'_1$
13.67	.08	0.5	2.51	15.5	- 9	77	$C_1C'_1dc'_1$
17.48	4.23	22.7	1.18	6.3	+ 19	73	$C_2C'_2rc'_2$
11.02	--	--	7.09	39.1	- 23	74	$DC'_2dc'_2$
12.96	5.11	36.3	1.10	7.8	+ 32	81	$B_1C'_1rc'_1$
16.47	16.19	97.4	0.15	0.9	+ 97	77	$B_1C'_1rc'_1$
14.42	9.21	56.4	1.91	11.7	+ 49	77	$B_2C'_1rc'_1$
14.13	3.96	26.4	0.87	5.80	+ 23	80	$B_1C'_1rc'_1$
10.69	4.39	36.6	1.32	11.0	+ 30.0	86	$B_1C'_1rc'_1$
20.20	106.64	527.9	0	0	+528	71	$AC'_2rc'_2$
10.59	6.19	51.4	1.46	12.1	+ 44	85	$B_2C'_1rc'_1$
12.55	--	--	3.45	21.6	- 13	78	$C_1C'_1dc'_1$
11.34	--	--	6.18	35.3	- 21	75	$DC'_2dc'_2$
12.09	--	--	4.17	25.6	- 15	77	$C_1C'_1dc'_1$
13.08	--	--	2.20	14.4	- 9	79	$C_1C'_1dc'_1$
15.57	5.64	33.2	1.44	8.5	+ 28	76	$B_1C'_1rc'_2$
18.45	2.11	9.8	3.09	14.3	+ 1	69	$C_2C'_2rc'_2$
7.52	--	--	6.22	45.3	- 27	82	$DC'_1dc'_1$
12.60	--	--	3.40	21.25	- 13	76	$C_1C'_1dc'_2$
16.61	--	--	3.11	15.8	- 9.5	72	$C_1C'_2dc'_2$
19.18	171.01	891.6	0	0	+892	73	$AC'_2rc'_2$
13.72	5.12	35.2	0.81	5.6	+ 32	81	$B_1C'_2rc'_1$
18.85	141.25	749.3	0	0	+749	73	$AC'_1rc'_2$
21.69	83.32	383.7	0	0	+384	69	$AC'_2rc'_2$
5.86	--	--	9.85	62.7	- 37.6	78	$DC'_1dc'_1$
16.13	1.55	8.5	2.12	11.6	+ 1.5	74	$C_2C'_2rc'_2$
14.29	0.43	2.7	1.89	11.7	- 4	77	$C_1C'_1dc'_1$
14.54	1.82	10.8	2.39	14.1	+ 2	76	$C2C'_2rc'_2$
7.56	--	--	3.31	30.5	- 18	89	$C_1D'dd'$
6.91	--	--	3.84	35.7	- 21	89	$DD'dd'$
21.34	57.30	268.0	0.04	0.2	+268	69	$AC'_2rc'_2$
16.42	19.87	103.9	2.71	14.2	+ 95	73	$B_4C'_2rc'_2$
22.80	146.30	641.7	0	0	+642	68	$AB'_1rc'_2$
15.45	4.60	27.5	1.27	7.6	+ 23	76	$B_1C'_1rc'_2$
15.36	0.35	2.1	1.40	8.4	- 3	76	$C_1C'_1dc'_2$
15.04	0.26	1.4	3.90	20.6	- 11	73	$C_1C'_2dc'_2$
18.82	37.84	196.2	0.47	2.4	+195	72	$AC'_2rc'_2$
20.24	74.17	366.5	0	0	+367	71	$AC'_2rc'_2$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Puntilla*[3/]	1,837	62°06'	152°45'	25.9	14.24	15.55
Radioville*	15	57°36'	136°09'	45.0	122.79	23.50
Rampart*	375	65°30'	150°15'	22.7	9.88	18.03
Rapids*	2,128	63°32'	145°51'	29.9	18.58	17.24
Richardson*	880	64°17'	146°22'	28.9	12.89	18.62
Ruby*	705	64°44'	155°26'	27.1	17.16	17.91
Salmon Creek Beach	20	58°19'	134°28'	40.9	106.8	20.09
Sand Point*	32	55°20'	160°30'	38.1	71.3	18.50
Savoonga*	35	63°41'	170°26'	23.5	9.95	11.50
Scotch Cap*	20	54°25'	164°45'	40.5	50.82	20.71
Seclusion Harbor*	20	56°33'	134°03'	43.1	111.9	22.17
Selawik	20	66°36'	160°02'	18.6	9.74	15.17
Seldovia	30	59°26'	151°43'	34.7	40.84	18.29
Seward*	76	60°07'	149°27'	39.4	68.98	19.88
Shaktolik	15	64°15'	161°09'	24.5	16.30	13.10
Shaw Island	8	58°12'	136°15'	43.3	105.0	21.81
Shearwater Bay*	5	57°21'	152°55'	40.2	96.84	19.76
Sheep Mountain*	2,280	61°48'	147°41'	28.8	11.01	16.42
Shemya*	92	57°42'	174°06'E.	38.8	26.15	18.70
Shingle Point*	120	68°57'	137°12'	13.1	7.32	12.44
Shishmaref*	16	66°14'	166°07'	20.5	8.00	12.40
Shungnak*	138	66°54'	157°02'	21.7	20.04	15.94
Sitka*	67	57°03'	135°20'	43.3	96.33	22.64
Sitkinak	53	56°33'	154°08'	39.9	53.4	18.09
Skagway*	18	59°27'	135°19'	41.1	29.86	20.87
Skwentna*	153	61°57'	151°10'	32.6	29.87	18.46
Slana	2,200	62°43'	143°55'	27.7	21.13	15.88
Sleetmute	285	61°42'	157°11'	25.9	23.44	15.46
Smeaton Bay	16	55°19'	130°47'	42.1	104.59	21.26
Smithers*	1,690	54°44'	127°06'	28.6	20.27	14.76
Snag*	1,925	62°22'	140°24'	21.4	14.07	17.20
Snowshoe Lake	2,500	62°02'	146°40'	21.5	11.6	12.58
Soldatna	85	60°29'	151°05'	31.8	19.1	16.97
Sparrevohn*	1,580	61°06'	155°34'	30.3	25.64	16.89
St. George Island*	100	56°36'	169°32'	36.3	29.27	16.61
St. Michael*	50	63°29'	162°01'	26.1	13.19	14.92
St. Paul Island*	22	57°09'	170°13'	35.2	24.24	15.94
Stampede	2,500	63°44'	150°22'	26.6	19.28	15.85
Sterling*	250	60°32'	150°45'	31.8	16.68	17.72
Stewart*	150	55°58'	129°58'	33.8	70.92	16.22
Stony River	221	61°46'	156°38'	28.3	22.03	16.98
Stuyahok	500	62°05'	161°00'	27.4	28.4	15.46
Sulzer	25	55°12'	132°49'	46.0	111.1	24.01
Summit*	2,401	63°20'	149°09'	25.8	22.25	15.51

NOTE: See footnotes at end of table.

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100(P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6 Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
13.55	--	--	1.97	12.7	- 7	79	$C_1C'_1dc'_1$
23.50	99.29	422.5	0	0	+423	67	$AB'_1r'_1$
9.88	--	--	8.15	45.2	- 27	74	$DC'_2dc'_2$
16.24	1.34	7.8	1.00	5.8	+ 4	76	$C_2C'_2rc'_2$
12.89	--	--	5.73	30.8	- 18	73	$C_1C'_2dc'_2$
13.78	--	--	4.13	23.1	- 14	75	$C_1C'_2dc'_2$
20.09	86.71	431.6	0	0	+432	71	$AC'_2rc'_2$
18.42	52.8	285.4	0.08	0.4	+285	74	$AC'_2rc'_2$
9.80	--	--	1.70	14.8	- 9	87	$C_1C'_1dc'_1$
20.71	30.11	145.4	0	0	+145	70	$AC'_2rc'_2$
22.17	89.73	404.07	0	0	+405	68	$AC'_2rc'_2$
9.74	--	--	5.43	35.8	- 21	79	$DC'_1dc'_1$
15.97	22.55	123.3	2.32	12.7	+114	74	$AC'_2rc'_2$
19.49	49.10	247.0	0.39	2.0	+246	71	$AC'_2rc'_2$
12.37	3.20	24.4	0.73	5.6	+ 21	84	$B_2C'_2rc'_2$
21.33	83.19	381.4	0.48	2.2	+380	69	$AC'_2rc'_2$
19.76	77.08	390.1	0	0	+390	72	$AC'_2rc'_2$
11.01	--	--	5.41	32.9	- 19.7	77	$C_1C'_1dc'_1$
17.76	7.45	39.8	0.94	5.02	+ 36	73	$B_1C'_2rc'_2$
7.32	--	--	5.12	41.2	- 25	85	$DC'_1dc'_1$
8.00	--	--	4.40	35.5	- 21	85	$DC'_1dc'_1$
15.45	4.10	25.7	0.49	3.1	+ 23	78	$B_1C'_1rc'_1$
22.64	73.69	325.5	0	0	+326	67	$AB'_1rb'_1$
17.97	35.31	195.2	0.12	0.7	+195	74	$AC'_2rc'_2$
16.57	8.99	43.1	4.30	20.6	+ 31	70	$B_1C'_2sc'_2$
16.97	11.41	61.8	1.49	8.1	+ 57	74	$B_2C'_2rc'_2$
15.16	5.25	33.1	0.72	4.5	+ 30.4	78	$B_1C'_1rc'_1$
14.49	7.98	51.6	0.97	6.3	+ 47	79	$B_2C'_1rc'_1$
21.23	83.33	392.0	0.03	0.1	+392	70	$AC'_2rc'_2$
13.32	5.51	37.3	1.44	9.8	+ 31	80	$B_1C'_1rc'_1$
14.07	--	--	3.13	18.2	- 11	75	$C_1C'_2dc'_2$
11.54	--	--	1.04	8.3	- 5	85	$C_1C'_1dc'_1$
14.31	2.13	12.6	2.66	15.7	+ 3	76	$C_2C'_2rc'_2$
16.44	8.75	51.8	0.45	2.7	+ 50	76	$B_2C'_2rc'_2$
16.34	12.66	76.2	0.27	1.6	+ 75	77	$B_3C'_1rc'_1$
11.81	--	--	3.11	20.8	- 12	80	$C_1C'_1dc'_1$
15.34	8.30	52.1	0.60	3.7	+ 50	78	$B_2C'_1rc'_1$
15.11	3.43	21.6	0.74	4.7	+ 19	78	$C_2C'_1rc'_1$
13.70	--	--	4.02	22.7	- 14	75	$C_1C'_2dc'_2$
16.10	54.70	337.2	0.12	0.73	+337	77	$AC'_1rc'_1$
15.44	5.05	29.7	1.54	9.1	+ 24	76	$B_1C'_2rc'_2$
14.56	12.94	83.7	0.90	5.8	+ 80.2	79	$B_2C'_1rc'_1$
24.01	87.09	362.7	0	0	+363	66	$AB'_1rb'_1$
15.09	6.74	43.5	0.42	2.7	+ 42	79	$B_2C'_1rc'_1$

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Summit Nike Site	3,980	61°15'	149°33'	29.3	30.7	12.69
Sunrise*[3/]	50	60°55'	149°35'	33.8	35.4	17.87
Susitna*	40	61°30'	150°40'	36.0	28.6	19.76
Taku Pass*	175	58°33'	133°41'	39.0	60.3	20.83
Talkeetna*	345	62°18'	150°06'	33.2	28.85	18.70
Tanaga Island	145	51°45'	178°02'	39.1	44.67	18.91
Tanacross*	1,546	63°24'	143°19'	23.5	10.02	17.52
Tanalian Point*	308	60°13'	154°22'	35.2	21.66	18.94
Tanana*	232	65°10'	152°06'	23.9	13.03	17.52
Telegraph Creek*	550	57°54'	131°09'	25.9	12.59	14.33
Teller*	10	65°16'	166°21'	24.7	11.92	13.54
Tenakee	19	57°47'	135°12'	42.8	68.41	21.01
Terrace*	719	54°28'	128°35'	36.1	47.18	17.91
Thane	20	58°15'	134°21'	41.5	81.5	19.54
Thompson Pass*	2,700	61°07'	145°44'	28.3	88.66	13.11
Thornbrough*	99	55°12'	162°43'	37.5	33.10	18.07
Tiekel	2,500	61°20'	144°55'	27.6	21.2	17.37
Tok	1,632	63°20'	143°02'	23.3	12.24	16.74
Tonsina	1,500	61°38'	145°11'	26.6	12.97	15.79
Tree Point*	36	54°48'	130°56'	45.8	96.67	23.94
Trims Camp*	2,408	63°26'	145°46'	26.5	36.11	17.29
Tunnel	500	60°41'	149°02'	37.3	44.67	17.94
Tyonek*	50	61°05'	151°15'	35.3	23.2	19.57
Uganik Bay*	50	57°43'	153°19'	40.7	42.06	20.24
Umiat*	337	69°22'	152°08'	11.1	5.51	11.34
Umnak	130	53°23'	167°54'	29.3	38.8	19.77
Unalakleet*	14	63°54'	160°47'	26.7	13.66	16.10
Unalaska	15	53°52'	166°31'	40.5	60.97	19.05
University Experiment Station*	481	64°51'	147°52'	25.6	13.37	18.31
Unuk River	5	56°04'	131°06'	40.5	118.82	18.94
Valdez*	15	61°07'	146°16'	35.6	62.05	18.62
Venetie	620	67°00'	146°34'	17.8	9.85	17.00
Venta	150	59°50'	150°58'	37.6	24.41	19.00
View Cove*	13	55°04'	133°04'	46.3	161.87	24.09
Wainwright*	29	70°40'	160°00'	11.7	4.10	8.58
Wales*	9	65°37'	168°03'	21.0	10.54	11.65
Wasilla	400	61°35'	149°28'	35.0	17.21	17.79
Whale Island*	46	57°58'	152°46'	39.8	54.03	19.69
Whitehorse*	2,103	60°43'	135°04'	30.8	10.05	18.23
White Mountain	50	64°41'	163°24'	27.0	15.36	16.10
Whittier*	31	60°47'	148°41'	39.0	163.74	19.57
Wild Lake	2,200	67°29'	151°36'	15.7	12.23	13.16
Willow	600	61°45'	150°00'	32.4	29.16	17.28
Windham	6	57°32'	133°29'	41.2	100.10	19.85

NOTE: See footnotes at end of table.

Six stations in Alaska and adjacent Canada--Continued

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\,(P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
11.75	18.01	141.9	0.94	7.4	+138	84	$AC'_1rc'_1$
16.02	17.53	98.1	1.85	10.4	+ 92	75	$B_4C'_2rc'_2$
18.40	8.84	44.7	1.36	6.9	+ 41	72	$B_2C'_2rc'_2$
20.28	39.47	189.5	0.55	2.6	+188	70	$AC'_2rc'_2$
17.28	10.15	54.3	1.42	7.6	+ 50	73	$B_2C'_2rc'_2$
18.21	25.76	136.2	0.70	3.7	+134	73	$AC'_2rc'_2$
9.92	--	--	7.60	43.4	- 26	75	$DC'_2dc'_2$
14.71	2.72	14.4	4.23	22.3	+ 1	73	$C_2C'_2sc'_2$
13.03	--	--	4.49	25.6	- 15	75	$C_1C'_2dc'_2$
9.49	--	--	4.84	33.8	- 20.3	81	$DC'_1dc'_1$
9.76	--	--	3.78	27.9	- 17	83	$C_1C'_1dc'_1$
20.93	47.40	225.6	0.08	0.4	+225	70	$AC'_2rc'_2$
16.50	29.27	163.4	1.41	7.9	+159	75	$AC'_2rc'_2$
19.54	61.96	317.1	0	0	+317	72	$AC'_2rc'_2$
13.11	75.55	576.3	0	0	+576	84	$AC'_1rc'_1$
17.13	15.03	83.2	0.94	5.2	+ 80.1	74	$B_4C'_2rc'_2$
14.27	3.83	22.0	3.10	17.8	+ 11	75	$C_2C'_2sc'_2$
12.24	--	--	4.50	26.9	- 16	77	$C_1C'_2dc'_1$
10.19	--	--	5.60	35.5	- 21	78	$DC'_1dc'_1$
23.94	72.73	303.8	0	0	+304	66	$AB'_1rb'_1$
13.19	18.82	108.8	4.10	23.7	+106	81	$AC'_2sc'_1$
16.39	206.73	149.0	1.55	8.6	+144	74	$AC'_2rc'_2$
16.31	3.63	18.5	3.26	16.7	+ 8.5	72	$C_2C'_2sc'_2$
18.54	21.82	107.8	1.70	8.4	+103	71	$AC'_2rc'_2$
5.31	--	--	6.03	53.2	- 32	88	DC'_1dd'
19.69	19.03	96.3	0.08	0.4	+ 96	72	$B_4C'_2rc'_2$
12.91	--	--	3.19	19.8	- 12	78	$C_1C'_1dc'_1$
18.59	41.92	220.1	0.46	2.4	+219	73	$AC'_2rc'_2$
11.93	--	--	6.38	34.8	- 21	74	$DC'_2dc'_2$
18.70	99.88	527.3	0.24	1.3	+526	73	$AC'_2rc'_2$
18.50	43.43	233.2	0.12	0.6	+233	73	$AC'_2rc'_2$
9.85	--	--	7.15	42.1	- 25	76	$DC'_2dc'_2$
15.50	5.41	28.5	3.50	18.4	+ 18	73	$C_2C'_2sc'_2$
24.09	137.78	571.9	0	0	+572	66	$AB'_1rb'_1$
4.10	--	--	4.48	52.2	- 31	96	$DD'dd'$
10.39	--	--	1.26	10.8	- 6	87	$C_1C'_1dc'_1$
15.48	--	--	2.31	13.0	- 8	75	$C_1C'_2dc'_2$
19.57	34.34	174.4	0.12	0.6	+174	72	$AC'_2rc'_2$
10.05	--	--	8.18	44.9	- 26.9	74	$DC'_2dc'_2$
12.13	--	--	3.97	24.7	- 15	78	$C_1C'_1dc'_1$
19.57	144.17	736.7	0	0	+737	72	$AC'_2rc'_2$
11.07	--	--	2.09	15.9	- 9.5	83	$C_1C'_1dc'_1$
14.43	11.88	68.8	2.85	16.5	+ 59	76	$B_2C'_2rc'_2$
19.85	80.25	404.3	0	0	+404	72	$AC'_2rc'_2$

Table 1.--*Location and climatic description for*

Station name[1/]	Elevation	Latitude (North)	Longitude (West)	Mean annual temperature	Mean annual precipitation (P)	Potential evapotranspiration (PET)
	Feet			Degrees F.	Inches	Inches
Wiseman* [3/]	1,286	67°26'	150°13'	22.0	15.36	16.57
Wonder Lake	2,000	63°28'	150°52'	31.8	19.50	18.48
Woody Island*	101	57°45'	152°20'	41.9	50.31	21.06
Wosnessenski	25	55°13'	161°21'	42.2	39.52	22.96
Wrangell*	37	56°28'	132°23'	43.7	82.90	22.60
Yakataga*	27	60°05'	142°30'	39.7	106.9	19.80
Yakutat*	28	59°31'	139°40'	39.3	134.15	19.80

1/ Spelling and location of station names are according to U.S. Geological Survey map E of Alaska, 1954.

2/ Thornthwaite's climatic type symbols.

3/ Asterisk denotes a climatic station for which complete water balance data are on file at the Institute of Northern Forestry, Juneau, Alaska.

A very cold climate (D D'dd'; i.e., semiarid, tundra, little or no water surplus, temperature efficiency normal to tundra) extends along most of the Arctic coast eastward from Point Lay. Here, mean annual temperature is about 10° F., precipitation only 5 or 6 inches per year, almost entirely snow. Climate near the tops of the high Rocky Mountains and temperatures on Mount Washington may approach this severity. In western Alaska, both temperature and precipitation decrease to the northward. Other generalizations are difficult, probably because continental, oceanic, and topographic influences on weather cause considerable variation among data from neighboring climatic stations.

Monthly PET at University Experiment Station, computed by three widely used estimating methods, is compared in figure 2. Annual PET by these methods agrees rather closely (Penman, 15.70 inches; evaporation pan, 18.68 inches; Thornthwaite, 17.87 inches). Papadakis (1961) estimated 15.75 inches PET at Fairbanks whereas Patric (1967) estimated 15.60 inches, using Hamon's (1964) equation. These annual figures are consistent with other comparisons which usually report annual values of PET by Thornthwaite's method higher than other estimates. Relative humidity strongly influenced Penman and evaporation pan estimates of monthly PET but could not influence Thornthwaite estimates which are based solely on temperature. Thus, figure 2 shows Thornthwaite estimates of PET low during the least humid months of May and June, highest during the more humid months of July, August, and September.

Figure 3 is a generalized map of PET for Alaska. The isolines of PET must be interpreted very carefully since the station values on which these lines are based were heavily biased to sea-level and valley-bottom climates. The climatic records for high-elevation stations are few, commonly of short

Actual evapotranspiration (AET)	Surplus P-PET	Index of humidity $Ih = \frac{100\,(P-PET)}{PET}$	Deficit PET-AET	Index of aridity $Ia = \frac{100\,(PET-AET)}{PET}$	Moisture Index MI=Ih-0.6 Ia	Summer need	Climatic type[2/]
Inches	Inches		Inches			Percent	
11.34	--	--	5.23	31.6	- 19	77	$C_1C'_1dc'_1$
17.71	1.02	5.5	0.77	4.2	+ 3	74	$C_2C'_2rc'_2$
20.59	29.25	138.9	0.47	2.2	+137	70	$AC'_2rc'_2$
22.68	16.56	72.1	0.28	1.2	+ 71	67	$B_3B'_1rb'_1$
22.56	60.30	266.8	0.04	0.2	+267	68	$AB'_1rc'_2$
19.80	87.10	439.9	0	0	+440	72	$AC'_2rc'_2$
19.80	114.35	577.5	0	0	+578	72	$AC'_2rc'_2$

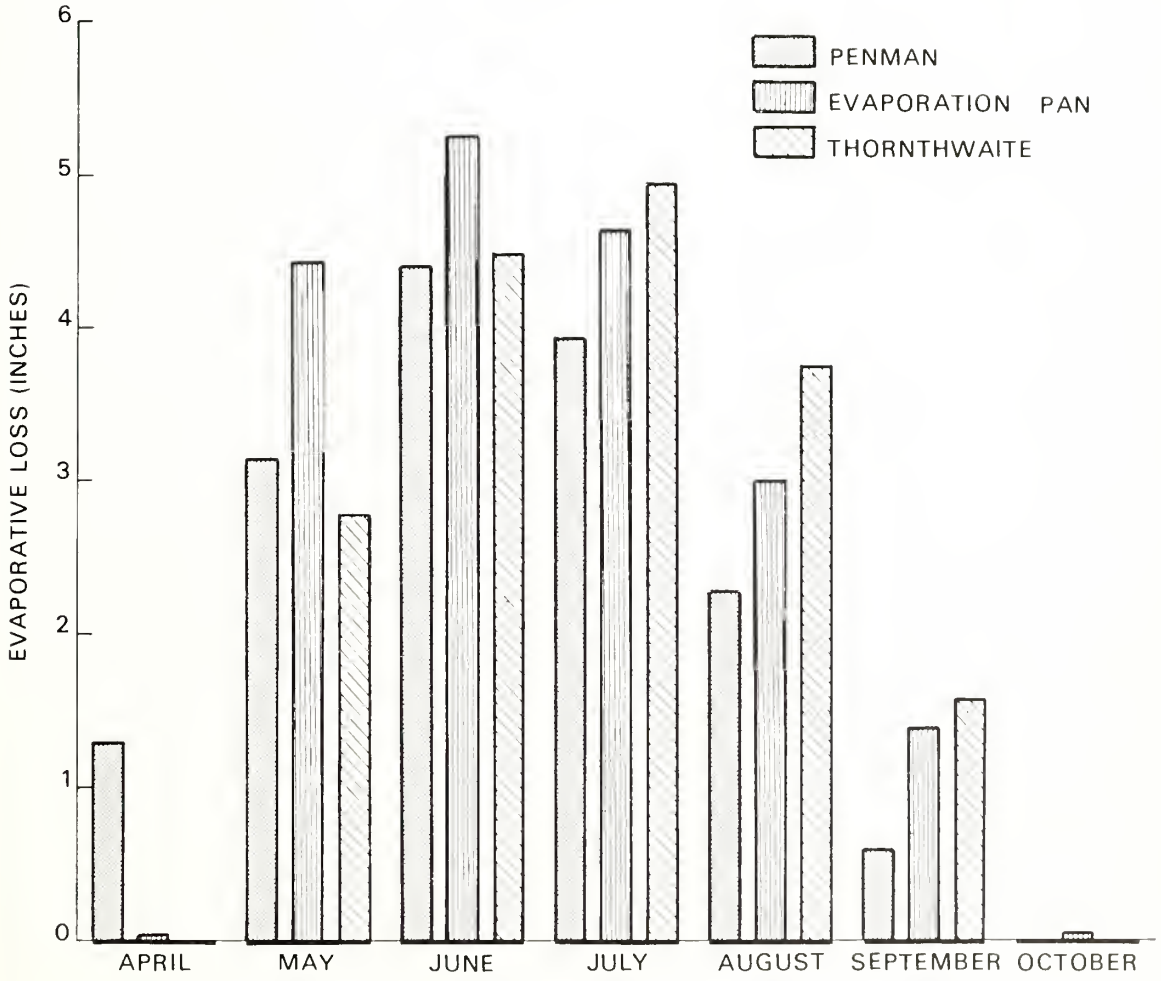

Figure 2.--*Estimates of potential evapotranspiration for University Experiment Station near Fairbanks, Alaska. Results by these three widely used methods are based on not less than 10 years of average monthly climatic data. This is the only station in Alaska for which long-term data are published to make this comparison possible.*

duration, and sometimes of questionable quality. Comparisons of PET were possible between 22 high-elevation stations and nearby sea-level or valley-bottom stations. Differences between PET and elevation for these stations are plotted in figure 4. The line drawn through these plotted points suggests that PET decreases about 1 inch per year per 500 feet of elevation.

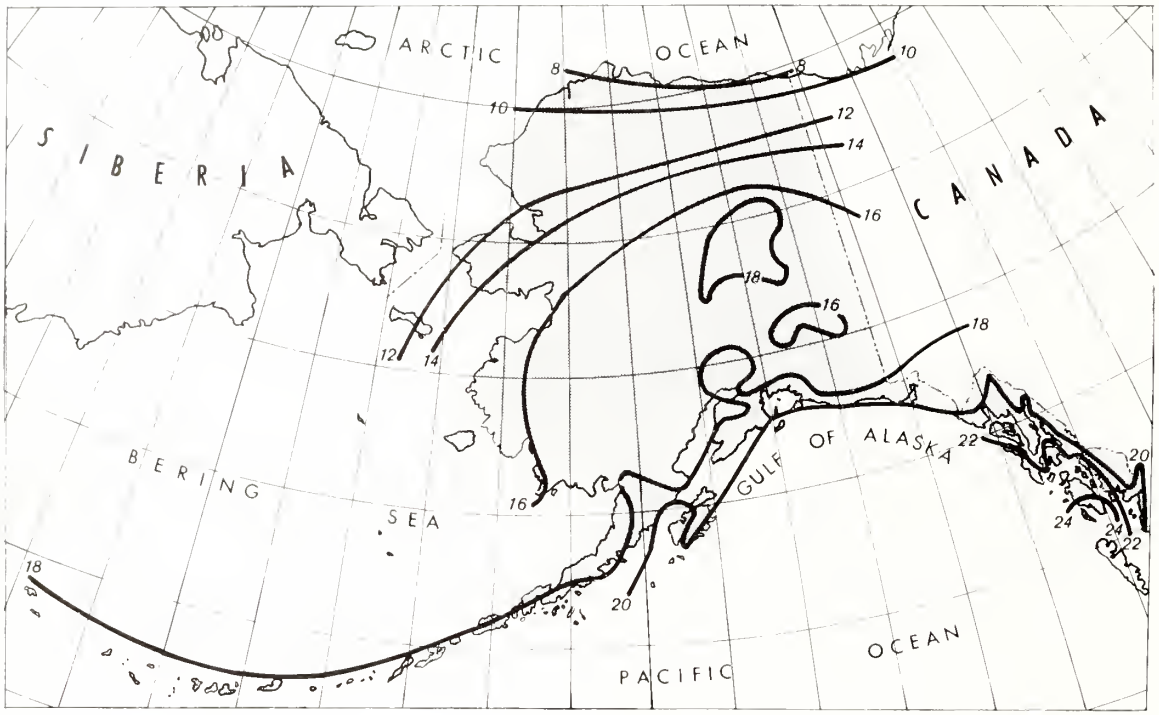

Figure 3.--*Potential evapotranspiration (PET) in Alaska. These lines, showing yearly evaporative loss in inches, are based solely on valley and sea-level climates.*

DISCUSSION

These estimates of PET must be considered first approximations which will be improved as better equations are developed to make more effective use of improved, more abundant, climatic data.

The influence of elevation on PET needs clarification, especially in a State as mountainous as Alaska. The hills and mountains of the interior are not represented in figure 3 because most interior climatic stations are along major rivers and represent only valley climates. The only stations reporting climatic data at high elevation in the interior (Summit Nike Site and Bonanza Mine) suggest a perhumid tundra climate above approximately 4,000-foot elevation. This climate is sufficiently wet and cold to nourish glaciers, which abound in the Alaska Range but which are smaller and occur less frequently in the drier climate of the Brooks Range. For coastal Alaska, the data in table 1 describe only stations near sea level and below the 3,000-foot timberline. Permanently snowcapped, extensively glacierized mountains also evidence a cold, wet climate at high elevation which is wholly unrepresented in figure 3.

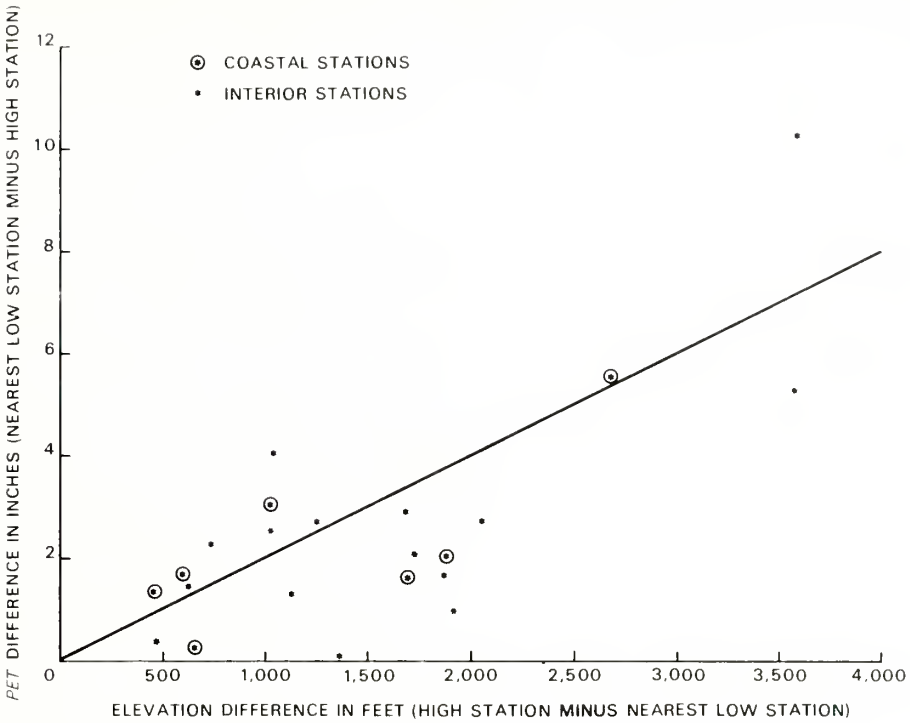

Figure 4.--*Effect of elevation on potential evapotranspiration (PET). Each plotted point shows how PET decreased with increasing elevation at the 22 stations where this comparison was possible. The 2:1 line was not statistically fitted to the data.*

The suggestion that PET decreases about 1 inch per year per 500 feet of elevation cannot be checked in the literature. There are, however, many studies of elevation-temperature relations and Thornthwaite's method of computing PET is based solely on temperature. It is an ecological truism that temperature on mountains decreases about 1° F. per 300 feet of elevation. Spurr (1964), for example, reported that temperature on east coast mountains decreases 3° F. per 1,000 feet of elevation. In maritime California, this increase is only 1° to 1-1/2° F. per 1,000 feet of elevation, a modifying effect of onshore Pacific winds. Table 1 permits similar temperature comparisons of Anchorage to Summit Nike Site, Kennecott to Bonanza Mine, and Valdez to Thompson Pass. These comparisons show average annual temperatures decreasing 1° F. per 370 to 650 feet of elevation. Because our temperature-elvation relations concur with those from other parts of the country, the PET-elevation relation suggested in figure 4 is at least of the correct magnitude.

Ideally, natural vegetation should reflect local climatic influences. For example, Thornthwaite and Mather (1955) demonstrated a close correlation of natural tree and grass vegetation to the moisture index along the 41st parallel in the United States. Hare (1950) reported no obvious correlation between

moisture provinces and forest divisions of the subarctic Labrador-Ungava Peninsula. Eastern Canada, however, does not have the large differences of rainfall found in Alaska. A belt of heavy rainfall extends along the southern shoreline from British Columbia westward to the end of the Aleutian chain. Within this fringe of perhumid climate, a dense western hemlock-Sitka spruce forest extends west to the Kenai Peninsula. Southwest from the Kenai Peninsula, Sitka spruce extends to Afognak Island and is invading Kodiak Island. Within this forest region, average PET for 68 stations is 21.27 inches, with a standard deviation of ± 1.61 inches. A few plantations of Sitka spruce on the Aleutian Islands have survived but they have grown very slowly. Note in table 1 the similarity of climate on Afognak, where Sitka spruce thrives, and on Adak, where one of these abortive plantations still exists. Our data suggest that failure of the coastal forest to thrive west of existing boundaries must be explained in terms other than temperature or amount and distribution of precipitation.

Heavy precipitation along the coastal perhumid belt becomes much lighter within relatively short distances from the Pacific Ocean, as shown in the following comparison of paired stations:

Precipitation at stations having perhumid climate	Precipitation at nearest station in drier climate	Distance apart
(Inches)	(Inches)	(Miles)
158 (Chignik)	17 (Port Heiden)	45
164 (Whittier)	14 (Anchorage)	50
89 (Thompson Pass)	21 (Teikel)	35
61 (Haines)	21 (Klukwan)	25
51 (Eldred Rock)	11 (Atlin)	70
80 (Alice Arm)	19 (New Hazelton)	85

In forested areas, this transition from heavy to light precipitation is distinctly marked by a change from western hemlock-Sitka spruce to the spruce-birch-aspen forest of the interior. Commercial stands of this interior forest are found along most major streams east of longitude 160° W. and south of the Arctic Circle (Hutchison 1967). Although annual precipitation rarely exceeds 15 inches, and may be as low as 6 inches within the commercial forest region of the interior, PET in this region ranges from 15.5 to 19.8 inches. Commercial timber, much of which occurs along major rivers (Hutchison 1967), may use moisture from water tables in addition to local precipitation for their water supply. These observations seem to be consistent with the widely accepted view (Hare 1950) "that the northern forests are governed in their growth by temperature and that precipitation is everywhere adequate to supply the needs of the growth possible under such cool conditions." Nevertheless, annual rings of reduced width occur[7/] that superficially appear to be associated with the

[7/] Personal communication from Wilbur A. Farr, Research Forester, Institute of Northern Forestry.

record low precipitation during 1958 and other dry years. However, the relation of growth ring width to various site factors, including precipitation and temperature, is poorly understood in the interior. Spruce-birch-aspen forests exist where PET is as low as 14 inches per year but rarely in commercial stands and usually associated with tundra vegetation. In fact, tundra mixed with scrubby tree cover should be expected wherever annual PET is less than 16 inches. These observations are consistent with Hare's findings for eastern Canada (Thornthwaite and Mather 1955) as shown in table 2.

Table 2.--*A comparison of potential evapotranspiration in natural vegetation of eastern Canada and interior Alaska*

Vegetation type	Potential evapotranspiration	
	Eastern Canada	Interior Alaska
	- - - - - - - Inches - - - - - - -	
Tundra	12.2	14.52 ± 2.42[1/]
Mixed tundra and noncommercial forest	12.2 - 16.5	16.51 ± 1.49
Commercial forest	16.5	17.76 ± .86

[1/] Mean and standard deviation for all stations.

Perhaps the higher PET values for Alaska are due to the aforementioned bias in station location, although ocean currents, topography, and prevailing airmass genesis actually may cause an Alaskan climate warmer than that of the eastern part of the continent at the same latitude.

More refined statistical treatment seems unwarranted since these data were collected over varying timespans by hundreds of observers having different equipment and training. Studies specifically designed to correlate vegetation and climate probably will relate natural plant cover to PET more as reported for eastern Canada.

Funsch (1964) used 16-year mean temperatures to derive growing season distribution of degree-days for 22 stations in the commercial forest zone of interior Alaska. PET calculated for the same stations also was derived from mean temperatures but from records collected over varying spans of time. To test the influence of timespan on temperature records, temperatures used in the PET calculations were converted to degree-days. Funsch's mean for all stations was 1,430 degree-days, a value little different from 1,438 for the same stations derived from PET temperature data. Although varying lengths of record had little effect on the degree-days, PET was much less variable as an

index of climate. For the 22 stations, coefficient of variation averaged almost 20 percent for growing season degree-days, a little over 5 percent for annual PET. Thus, even though temperature is recognized to govern growth of northern forests, PET reflects forest distribution better than temperature data alone.

An interesting anomaly occurs along the Arctic coastal plain where evaporative demand considerably exceeds precipitation but soil almost always remains wet, even saturated, throughout the short summer. The moss and lichen plants of this tundra region apparently use water at slower rates than does vegetation of warmer regions. Tundra plants function more like mulch than like transpiring vegetation, and under these conditions the whole Thornthwaite formula seems to break down.[8/] Shallow thawing of permafrost under the tundra vegetation also may contribute moisture to these very wet soils.

The few checks available suggest that PET by Thornthwaite's method provides valid estimates of this measure of climate. Our evidence supports Hare's (1950) conclusion that growth of the northern forest is governed by temperature. In terms of thermal efficiency, commercial forest can be expected in warm microthermal climates, whereas noncommercial forest mixed with tundra can be expected in cold microthermal climates. Forest species, if found at all in tundra climates, are severely stunted. These close relationships of natural vegetation to the Thornthwaite climatic classification strengthen our confidence in PET as a key parameter of climate.

[8/] Personal communication from John R. Mather, President, C. W. Thornthwaite Associates, Centerton, N. J.

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Estimates and measurements of potential evapotranspiration (PET) by Thornthwaite's methods showed good agreement with estimates and measurements by other methods. Natural vegetation is closely related to climate. Vegetation distribution in the interior seems governed more by temperature than by moisture availability. The available data heavily bias classifications of climate to sea-level and valley-bottom conditions.

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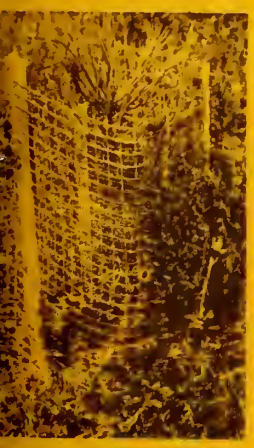
reclamation of nonsprouting greenleaf manzanita brushfields in the cascade range

by H. Gratkowski
and
Lyle Anderson



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Lyle Anderson was with the Rogue River National Forest, Forest Service, U.S. Department of Agriculture, as Timber Management Staff Assistant and is now retired.

INTRODUCTION

Several species of manzanita found in the Cascade Range, but onsprouting form of greenleaf zanita (*Arctostaphylos patula* ene)[1] is of special concern to esters in southwestern Oregon. hough it commonly occurs as ttered plants or clumps in mixture h other brush species, dense, atively pure stands of this manza- a occupy extensive areas of mercial forest land in the south- half of the Cascade Range.

Areas of such manzanita-infested est land are especially prevalent pumice and other volcanic soils the vicinity of Mount McLoughlin the Rogue River National Forest, where mixed stands of ponderosa pine and Douglas-fir were railroad-logged during 1920-25. The extensive cut-over areas failed to restock naturally with conifers. Instead, the disturbed areas were occupied by greenleaf manzanita that held the sites in a non-productive condition for more than 30 years.

This research paper gives results of small plot and aerial tests of herbicides on this manzanita and provides information on mechanical eradication as a reclamation method for the manzanita brushfields. The latter information is based upon approximately 10 years of practical experience on the Rogue River National Forest.

EXPERIMENTS WITH HERBICIDES

Tests With Ground Spray Equipment

Modern herbicides were considered especially promising for low-cost control of manzanitas in the mid-1950's; therefore, a screening test was set up to determine the effect of 2,4-D and 2,4,5-T on mature shrubs of this nonsprouting greenleaf manzanita.[2] Random samples of 20 shrubs each were sprayed to drip point during late July with one of six different formulations of low-volatile propylene glycol butyl ether (PGBE) esters[3] of 2,4-D or 2,4,5-T (table 1). Each herbicide was tested

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[1] Exact identity of this manza- a has not yet been established. has been variously identified as enleaf manzanita (*Arctostaphylos ula* Greene) and Howell manzanita *hispidula* Howell). It is prob- y an ecotype of the greenleafed zanita prevalent in central Oregon t has also been identified or list- as *A. patula* Greene, as pine man- ita (*A. parryana* var. *pinetorum* llins) Wiesl. & Schr.), as *A. ula* Greene ssp. *platphylla* (Gray) V. Wells, and as *A. obtusifolia* er. The nonsprouting characteris- , as compared to sprouting of the led form of greenleaf manzanita the Siskiyou Mountains, is of cial interest to foresters; this sprouting greenleafed manzanita be killed with herbicides at far s cost.

[2] Gratkowski, H. Effects of herbicides on some important brush species in southwestern Oregon. U.S.D.A. Forest Serv., Pacific Northwest Forest and Range Exp. Sta. Res. Pap. 31, 33 pp., illus. 1959.

[3] Commercial formulations of these herbicides were supplied by the Dow Chemical Company. Their cooperation is sincerely appreciated.

Table 1.--*Effects of a midsummer foliage spray of herbicides on non-sprouting greenleaf manzanita in the Cascade Range*

Treatment			Total plants sprayed	Plants with basal sprouts	Percentage of kill	
Herbicide	Concentration	Carrier			Top[1/]	Complete plant[2/]
	Aehg[3/]		Number	Percent	Percent	Percent
2,4-D	1	Water	20	0	99	85
2,4-D	1	Emulsion[4/]	20	0	97	80
2,4-D	2	Water	20	0	100	95
2,4-D	2	Emulsion[4/]	20	0	99	100
2,4,5-T	2	Water	20	0	96	85
2,4,5-T	2	Emulsion[4/]	20	0	95	95

[1/] Percentage of crown dead 3 months after spraying.

[2/] Percentage of shrubs completely dead 14 months after spraying; only a few green twigs were present on shrubs still alive at that time.

[3/] Pounds acid equivalent per hundred gallons.

[4/] 5 percent diesel oil.

in water carriers and in oil-in-water emulsions containing 5 percent black diesel oil by volume. New shoots were 2 to 3 inches long at time of treatment, most new leaves were fully developed, and berries were full size.

The tests (table 1) show that this nonsprouting form of greenleaf manzanita is readily killed with one application of either 2,4-D or 2,4,5-T, but 2,4-D is more effective and economical. Diesel oil emulsions were no more effective than water as a carrier for the phenoxy herbicides, but thorough coverage was more easily obtained with the emulsion. Complete spray coverage of all foliage on the exterior of the crown proved advisable, for ends of branches missed or sprayed too lightly remained alive for years after treatment, even though the rest of the crown died.

However, flagged plants[4/] in the screening tests did not resprout from other stems or from root crowns, and brush competition with associated conifers was appreciably reduced.

Next, a small, replicated minimum dosage test was installed during 1956 to determine the least amount of 2,4-D required per acre to insure a satisfactory kill of this green-leaved manzanita. A commercial formulation of low-volatile PGBE esters of 2,4-D was applied with a knapsack sprayer on replicated 1/100th-acre plots at rates of 1, 2, and 4 pounds ae[5/] per acre in

[4/] Plants with leaves that survived the spray treatment or with live stem sprouts produced after spraying.

[5/] Acid equivalent.

water and in emulsion carriers. Although this series of plots was destroyed in a mechanical brush clearing project before final evaluation, preliminary observation a year after treatment indicated that the minimum required dosage of 2,4-D was 2 to 4 pounds ae per acre in midsummer foliage spraying. This information was used in a 100-acre test of aerial spraying to control manzanita on the Rogue River National Forest.

Aerial Spraying

Three large plots were marked for aerial spraying on a manzanita-covered flat approximately 6 miles southeast of Butte Falls, Oregon. One plot was 60 acres in size; each of the other two was 20 acres. A small number of ponderosa pines (*Pinus ponderosa* Laws.) and Douglas-firs (*Pseudotsuga menziesii* (Mirb.) Franco) ranging from 2 to 25 feet in height were present on all three areas.

All three areas were sprayed with commercial formulations of isooctyl esters of phenoxy herbicides from a fixed-wing biplane on June 10, 1958 (table 2). The herbicides were applied in oil-in-water emulsions containing 1 gallon of black diesel oil in a total of 7 gallons of spray per acre. Weather conditions during spraying were partially overcast, cool, and calm. The manzanita shrubs were growing, a condition in which they were easily killed in screening tests.

Briefly, the aerial spray trials (table 2) indicate that a late spring aerial application of 3 pounds ae of low-volatile esters of 2,4-D per acre will insure an almost complete kill of this nonsprouting form of greenleaf manzanita in southwestern Oregon. Four pounds of 2,4-D per acre killed 96 percent of the large, mature manzanita shrubs; 2 pounds killed only 74 percent. Only a negligible amount of living foliage was found on surviving plants in the latter area, and none of these had basal sprouts. These results indicate that aerial application of 3 pounds ae of 2,4-D per acre will produce an acceptable degree of control for this species in brushfield reclamation projects. Helicopter application of this treatment would now cost about $6.50, including cost of chemicals, administration, and application of 8 gallons of spray per acre.

Both ponderosa pines and Douglas-firs on these spray areas sustained damage from the June treatment. Pines were more severely damaged than firs.

Reforestation After Aerial Spraying

Although aerial spraying is an effective method for killing this manzanita, brush control is only the first phase of any brushfield reclamation project. Reforestation is the second phase, and experience on this project has shown that animal damage can eliminate any conifers planted or seeded on a site and render useless even a perfect job of brush control.

Portions of the sprayed plots were planted with both ponderosa pine and Douglas-fir seedlings during the first fall after spraying. Almost all manzanita foliage was dead, and stems of the shrubs had died back about one-fifth of their length by the time the areas were planted. Before planting, cattle trampling and deer browsing of young trees were considered potential dangers to young conifers planted in the spray area. Therefore, the seedlings were planted under the crowns of the sprayed manzanita shrubs with the idea that the shrubs would die, harden, and form a natural barricade protecting the trees from deer browsing and cattle trampling. Unfortunately, rabbits were numerous on the site, and the plantings failed. The chemically killed brush evidently provided enough cover so that rabbits felt safe from predators and moved about freely beneath the dead brush. Three weeks after the areas were planted, a survey

Table 2.--*Effect of early June aerial applications of herbicides on nonsprouting greenleaf manzanita*

Treatment		Acres	Shrubs with stem sprouts	Shrub kill	
Chemical	Pounds/acre			Aerial parts	Complete plant
	Ae[1]		Percentage		
2,4-D	2	20	26	97	74
2,4-D	4	60	4	[2]100	96
2,4-D plus 2,4,5-T	2 plus 1	20	4	[2]100	96

[1]Acid equivalent.

[2]A few stem tips were alive on 2 of the 50 plants examined in each of these treatments.

revealed that 95 percent of the trees had been clipped off near ground level.

After this experience, District personnel decided that the dead brush would have to be windrowed and burned to eliminate the cover for rabbits before planting. With loose, sandy soil and dead brush, the clearing cost was only $15 to $18 per acre. The area was again replanted in the spring of 1963, and baiting for rabbits and rodents was provided as a continuing program. Survival from this planting ranged from a high of 60 percent in some areas to a low of 5 percent in others. Rabbits, deer, and gophers accounted for much of the loss.

Ten years' experience now indicates that the brushfields could have been aerially sprayed and planted with caged Douglas-firs and ponderosa pines in the shade of the dead brush. This would have saved at least 5 years in reforesting the site.

MECHANICAL CLEARING AS A RECLAMATION METHOD

In October 1958, when the aerial spray areas were treated, a similar stand of manzanita on a nearby 10-acre area was eradicated and piled by tractor. The piled and windrowed brush was burned. Cost of bulldozing under such conditions is now approximately $22 per acre.

Planted conifers sustained much less rabbit damage on the mechanically cleared area than under the chemically killed brush. Although rabbits browsed some trees near the edges, they rarely seemed to range beyond a chain (66 feet) from the protective cover--possibly from fear of predators. Survival of planted trees was noticeably better in this opening. Similar results have since been observed on additional mechanically cleared sites in other manzanita brushfields in this area.

Even in mechanically cleared areas, however, an undesirable number of trees may be killed or damaged by rabbits. Protection may be necessary to reduce such damage. On cleared sites in the Rogue River National Forest where rabbits may be a problem, newly planted trees are enclosed in 14-inch-tall, open-ended cylinders of ½-inch mesh hardware cloth (fig. 1). Each cage (cylinder) is approximately 7 inches in diameter. Initially, the upper portion of the cylinder is sometimes folded above the seedling to provide more complete protection (fig. 2). As the seedling develops, the top is unfolded to allow the tree to grow out of the cylinder. Cages are normally left in place for 3 years, with about 10 percent being lost to cattle and deer damage on a given site during the 3-year period. Since most cages are used repeatedly, cost of constructing and installing cages to protect 300 trees per acre has been estimated at about $30 per acre. Large-scale commercial production of such cages would undoubtedly reduce this cost appreciably.

Figure 1.--Cylindrical cage of 1/2-inch mesh hardware cloth protects planted trees from rabbit browsing on the Rogue River National Forest.

DISCUSSION

Experience on these projects on the Rogue River National Forest has shown that this nonsprouting form of greenleaf manzanita can be effectively controlled with aerial spraying. A satisfactory treatment is 3 pounds ae of low-volatile esters of 2,4-D per acre in either water or a diesel oil-in-water emulsion at a rate of 7 or 8 gallons of spray per acre. The spray may be applied during the growing season during spring and early summer, when this manzanita is most susceptible to herbicides. It seems entirely feasible now that such areas may then be planted, but the trees should immediately be protected in hardware cloth cages such as those described to protect the trees from rabbits. The cages should be left in place at least 3 years.

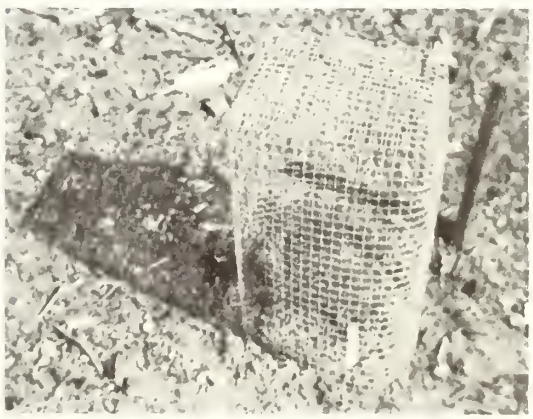

Figure 2.--Tops of cages are sometimes folded over small trees to provide more complete protection; they are unfolded later to allow tree to develop.

To release young conifers from competition of this manzanita, a much lower dosage should be both effective and feasible, for a smaller percentage of crown and shrub kill will satisfactorily release conifers. Experience indicates that release of overtopped Douglas-firs should be possible with an early spring aerial application of about 1.5 pounds ae of 2,4-D in either water or an oil-in-water emulsion containing approximately one-half gallon of diesel oil per acre. The shrubs should be sprayed as soon as possible after brush growth begins and the shrubs are relatively free of snow. Chemicals and aerial spraying to release Douglas-firs from this manzanita should cost approximately $6 per acre.

Safe and effective methods for releasing ponderosa pines from this manzanita on the western slope of the Cascade Range have yet to be developed. Early spring treatments such as that described for Douglas-fir above severely damage and kill many ponderosa pines.

In central Oregon, however, a satisfactory aerial spray treatment has been devised to release ponderosa pines from manzanita.[6/] There, 1¼ pounds ae of low-volatile esters of 2,4-D are applied per acre in an oil-in-water emulsion containing one-third gallon of No. 2 diesel oil per acre. A total volume of 8 gallons of spray is applied per acre, and 1 pint of emulsifier is added to each 100 gallons of spray. The spray is applied when manzanita is growing but before bud burst on the pines.

On sites where rabbit populations are large and rabbit browsing is apt to be a problem, mechanical eradication by piling and burning or other methods of brush removal should be considered. Such methods should also be considered in lieu of spraying and caging for sites where large numbers of trees are to be planted per acre. Trees planted under chemically killed brush should be caged, in most cases, and both planting and caging costs increase proportionately beyond the costs cited when more than 300 trees are planted per acre.

Caging usually will not be as imperative on completely cleared sites. This, however, may depend to a degree on species of rabbits present. Observation on the Rogue River National Forest indicates that brush rabbits (*Sylvilagus nuttallii* Bachman) are more timid than jack rabbits (*Lepus californicus* Merriam). In mechanically cleared areas, jack rabbits have been observed ranging all over the cleared area; while brush rabbits rarely ranged more than a chain (66 feet) from protective cover.

Even in many mechanically cleared areas, however, an undesirable number of trees have been lost or damaged by rabbits. Although caging of planted trees is expensive, cages will be desirable on many areas to protect the investment in clearing and planting costs, to increase survival of planted trees, and thus possibly shorten regeneration and rotation periods for the sites.

Where fire can be used safely, brush eradication similar to that resulting from mechanical clearing might be achieved at lower cost by burning chemically killed brush after aerial spraying.[7/] [8/] Before the

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Table 3.--*Approximate costs*[1] *per acre for alternative methods of brushfield reclamation in manzanita areas on the Rogue River National Forest*

Treatment	Methods of brushfield reclamation								
	1	2	3	4	5	6	7	8	9
	Dollars								
Aerial spraying[2]	6.50		6.50	6.50	6.50				6.50
Mechanical clearing		22.00	17.50	17.50		22.00	22.00	22.00	17.50
Burn windrows				2.00		2.00	2.00	2.00	2.00
Bait and trap							4.00		4.00
Planting	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
Caging trees					30.00			30.00	30.00
Total costs	31.50	47.00	49.00	51.00	61.50	49.00	53.00	79.00	85.00

[1] Based upon 1968 costs.

[2] Aerial application of 3 pounds ae of 2,4-D per acre.

sprayed brush is ignited, however, a good fire trail should be constructed with a bulldozer around the area to be burned, and adequate fire control equipment should stand by during burning. Burning should only be done by qualified fire control personnel.

Figures on relative costs of the methods discussed will undoubtedly be of interest to foresters considering brushfield reclamation projects in this and similar brush types. Costs of various operations and alternative methods of treatment based upon experience on the Rogue River National Forest are given in table 3. Not all of these were tried on specific areas, but all combinations of treatments listed are possible. Since these alternative treatments may be considered by other foresters, we have tried to provide the best estimates of reasonable costs based upon our experience in this brush type over the past 10 years.

SUMMARY

This nonsprouting form of *Arctostaphylos patula* Greene can be controlled with aerial applications of herbicides. A satisfactory treatment is 3 pounds ae of low-volatile esters of 2,4-D per acre in a diesel oil-in-water emulsion at a rate of 7 or 8 gallons of spray per acre. This spray should be applied during the growing season in spring or early summer when the manzanita is most susceptible.

To release young conifers from competition of manzanita, a much lower dosage is recommended. About 1.5 pounds ae of 2,4-D per acre in a water carrier or in an oil-in-water emulsion may be sufficient to provide acceptable results with a minimum of damage to Douglas-firs. Acceptable methods for release of ponderosa pines on the western slope of the Cascade Range have yet to be developed.

Where rabbit browsing is apt to be a problem, mechanical eradication by piling and burning or other methods of brush removal should be considered. Rabbits move about and browse trees planted under standing chemically killed brush in aerially sprayed areas. Where fire can be used safely, a result similar to mechanical eradication might be achieved at lower cost by burning chemically killed brush after aerial spraying. Cylindrical cages of ½-inch mesh hardware cloth placed around each tree may further reduce mortality by preventing browsing of the trees by rabbits.

Gratkowski, H., and Anderson, Lyle.
1968. Reclamation of nonsprouting greenleaf manzanita brushfields in the Cascade Range. U.S.D.A. Forest Serv. Res. Pap. PNW-72, 8 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

Small plot and aerial spray trials have shown that nonsprouting greenleaf manzanita in the Cascade Range can be killed by a single aerial application of 3 pounds ae of 2,4-D per acre. Conifers planted amid the dead shrubs should be caged in hardware cloth cylinders for protection from rabbit browsing. Less rabbit damage was sustained by trees on mechanically cleared sites than under chemically killed brush. Approximate costs per acre are given for alternative methods of brushfield reclamation.

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Alaska - Cedar

A Bibliography with Abstracts

Compiled by A.S. HARRIS

Pacific Northwest Forest and Range Experiment Station
Institute of Northern Forestry Juneau, Alaska
U.S. Department of Agriculture - Forest Service
U.S.D.A. Forest Service Research Paper PNW-73 1969

FOREWORD

This bibliography contains references to North American and European literature containing information about Alaska-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach).

References are listed alphabetically by author, and abstracts are given for many of those considered more significant. A subject matter index is included on pages 42-45, and a list of scientific and common names of tree species mentioned is on pages 46-47.

The single, most useful source of references for the bibliography was "Forestry Abstracts," followed by "Bibliography of Agriculture." Thanks are due to reviewers for pointing out many additional references not found by the compiler and to others who helped in preparation.

The compiler would appreciate learning of additional articles on Alaska-cedar not included here.

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   Parks, large gardens and pleasure grounds, smaller gardens, rock gardens, and windbreaks.

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   Alaska-cedar wood is highly regarded in Canada and the U.S. for interior woodwork and paneling. The yellow timber has a fine texture and is responsive to finishing treatments. Freshly cut wood has a strong but pleasant aromatic scent which is generally absent in seasoned material. The wood weighs about 29 pounds per cubic foot in seasoned condition. Shrinkage in drying is slight, and the wood is noted for dimensional stability in service. It is used for both construction and decoration.

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   Alaska-cedar occurs in the park up to 7,000-foot elevation. It is common on northern exposures, along streams, and in basins at the head of canyons. It also grows on crests and ridges where frequent showers and fogs supply the moisture it demands. In sheltered localities, it grows to a height of 80 feet, but is commonly small, with a bent and twisted stem and somewhat scrubby appearance. A general description is given.

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Alaska-cedar seasons readily, and 1- and 1-1/2-inch stock may be dried successfully by the same schedule as that for western redcedar. Two-inch stock, particularly wide clears, requires more careful treatment, and a schedule is given.

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Alaska-cedar is the highest reaching tree species, ascending beyond 7,000 feet and growing out of rock cliffs in the Olympic rain shadow. Krummholz of this species have advantages over others in severe alpine environments because of extremely durable wood and more flexible branchlets that are less apt to be scoured off. Roots of Krummholz Alaska-cedar may extend 100 feet. Root sprouting and layering probably explain scrubline development of Alaska-cedar shrubs whose foliage may form circles of nearly 50-foot diameter. The condition of Alaska-cedar at timberline throughout its range is discussed.

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27. Bancroft, Hubert Howe.
1886. History of Alaska, 1730-1885. 775 pp. San Francisco: The History Co. Publishers. (Reprinted, New York: Antiquarian Press.)

Yellow-cedar is the most valuable timber found on some of the islands in the Alexander Archipelago and in the neighborhood of Sitka, and frequently attains a height of 100 feet and diameters of 5 or 6 feet. The wood is in demand by shipbuilders and cabinetmakers because of its fine texture, durable quality, and aromatic odor.

28. Bannan, M. W.
1950. The frequency of anticlinal divisions in fusiform cambial cells of *Chamaecyparis*. Amer. J. Bot. 37: 511-519.

Frequency of anticlinal divisions in fusiform cambial cells of *Chamaecyparis lawsoniana*, *C. thyoides*, and *C. nootkatensis*, was studied. Nearly all anticlinal divisions were of the pseudotransverse type, and occurred as often as three or four times a year when growth was vigorous.

29. _____
1950. Abnormal xylem rays in *Chamaecyparis*. Amer. J. Bot. 37: 232-237.

Abnormal rays, such as reported previously for *Thuja*, *Juniperus*, and *Libocedrus*, occur also in *Chamaecyparis*. They are larger than ordinary rays and differ in the arrangement and structure of the cells. The abnormal rays are described in detail. Three species of *Chamaecyparis* were studied; *C. lawsoniana*, *C. thyoides*, and *C. nootkatensis*.

30. _____
1951. The annual cycle of size changes in the fusiform cambial cells of *Chamaecyparis* and *Thuja*. Can. J. Bot. 29: 421-437.

In stems exceeding a few inches in diameter, most of the pseudotransverse divisions involved in the multiplication of fusiform cambial cells occur toward the end of the growing season. Often these aestival transverse divisions are immediately followed by extensive elongation of the newly formed cambial cells, especially at their overlapping tips. In the succeeding year, relatively slight elongation ensues during the development of the first quarter of the annual ring, but through the succeeding quarters the amount of extension increases and is usually maximal in the final quarter. The actual rates of elongation remain undetermined. The multiplication of fusiform initials is accompanied by loss, most of the failure taking place during the last quarter. Generally the fusiform initials with the most extensive ray contacts survive and enlarge, and those with poor ray associations fail or are reduced to potential ray initials. The elongations and multiplication of fusiform initials tend to produce local ray deficiencies. Reduction of the fusiform initials with the poorest ray contacts to ray initials, rectifies to a varying extent the ray shortages in those areas. (Author's summary.)

31. _____
1951. The reduction of fusiform cambial cells in *Chamaecyparis* and *Thuja*. Can. J. Bot. 29: 57-67.

The loss of fusiform initials from the cambium, which is of frequent occurrence in all parts of the tree, takes place in different ways. Some cambial cells seem gradually to fail and are shortly lost from the cambium by maturation into more or less imperfect xylem or phloem elements. The majority are transversely subdivided by one or a succession of anticlinal

divisions which begin near the center of the fusiform initial and usually extend to the daughter cells. The resulting segments shorten through the following periclinal divisions, some disappearing during the process of shortening and others undergoing transformation to rays initials. Nearly all new rays in the secondary body originate in this manner. (Author's summary.)

32. _____
1952. The microscopic wood structure of North American species of *Chamaecyparis*. Can. J. Bot. 30: 170-187.

The trends in variation in different parts of the tree with regard to tracheid and ray cell dimensions, size and distribution of rays, size and arrangement of pits, and thickness of cell walls were compared between three species of American *Chamaecyparis* and other Cupressaceae. Intraspecific variability is usually so extensive that specific ranges overlap widely. No single microscopic character is entirely diagnostic, but certain structural features are valuable when used together.

33. _____
1966. Spiral grain and anticlinal divisions in the cambium of conifers. Can. J. Bot. 44: 1515-1538.

Discusses the orientation of pseudotransverse divisions in the cambium of conifers and presents in tabular form the sequels to 40,000 pseudotransverse divisions, with reference to failure or lineal continuation of sister fusiform initials arising therefrom, in 25 conifer species, including Alaska-cedar.

34. _____ and Bayly, Isabel L.
1956. Cell size and survival in conifer cambium. Can. J. Bot. 34: 769-776.

Discusses the process of division and survival of fusiform initials in conifers. Length of fusiform initials at pseudotransverse division, and information on surviving and failing fusiform initials of 15 conifers, including Alaska-cedar, are tabulated.

35. _____ and Whalley, Barbara E.
1950. The elongation of fusiform cambial cells in *Chamaecyparis*. Can. J. Res. 28C(3): 341-355.

After their origin, sister fusiform initials usually elongated rapidly. Rate and amount of extension varied, often proceeding in a somewhat periodic fashion. Growth appeared to be apical, "intrusive" in the sense that the elongating tips thrust between other cells. No evidence was found to support the theory of simultaneous elongation of considerable portions of adjoining walls by "symplastic" growth.

36. Bannister, M. H.
1962. Prospects for selection in the cypresses. New Zeal. J. Forest. 8: 545-559.

Reviews the distribution and characteristics of *Cupressus* and *Chamaecyparis*, the occurrence of natural hybrids, and the possibility of breeding for superior qualities.

37. Bauger, E., and Smitt, A.
1960. Et treslags- og proveniensforsok pa Stad. (An experiment on tree species and provenances on Stad.) Medd. Vestland. Forstl. Forsoekssta. 11(2)34: 61-121, illus. (In Norwegian.)

Alaska-cedar from Chichagof Island, Alaska, was planted in 1922 as 2-2 planting stock. Seventy percent survived. Most were about 40-50 cm. high but a few were 1.5 meters when sheltered. They are green and look healthy but have not been able to grow above the surrounding vegetation because of wind. Cones with seed were found on even the small plants. The species is not suitable for planting on the outer coast because of wind.

38. Becking, Rudy W.
1956. Die naturlichen Douglasien-Waldgesellschaften Washingtons und Oregons. (The forest associations of Douglas-fir in its natural range in Washington and Oregon.) Allg. Forst-und Jagdzeitung 127(2/3): 42-56, illus. (In German. English summary.)

Alaska-cedar is included in the tree species found in the subalpine salal-Pseudotsuga (Gaultherieto-Pseudotsugetum Subalpinum) association characteristic for elevations from 3,000 feet to timberline (7,000-8,000 feet) in Oregon and Washington.

39. Bender, F.
1963. Cedar leaf oils. Can. Dep. Forest., Forest Prod. Res. Br. Pub. 1008, 16 pp., illus.

Describes methods of producing oil from leaves of *Thuja occidentalis*, *T. plicata*, *Juniperus virginiana*, and *Chamaecyparis nootkatensis*, and gives data on yields, production, and prices. Some properties of the oil are tabulated, and a brief description is given of the industry in Canada and the U.S. with details of the main commercial outlets in Canada.

40. Benson, Gilbert Thereon.
1930. The trees and shrubs of western Oregon. Contrib. Dudley Herb. Vol. 2, 170 pp., illus. Calif.: Stanford Univ. Press.

Briefly reviews nomenclature and distribution of Alaska-cedar in Oregon. Alaska-cedar is listed, along with *Pinus albicaulis*, *Abies lasiocarpa*, and *Tsuga mertensiana*, as the most distinctive trees in the Hudsonian zone in the high peaks of the Cascade, Siskiyou, and Coast Ranges.

41. Berry, James B.
1924. Western forest trees. 212 pp., illus. New York: Dover Publ., Inc. (Corrected reprint of original publication by World Book Co., 1964)

42. Betts, H. S.
1929. The strength of North American woods. U.S. Dep. Agr. Misc. Pub. 46, 17 pp.

Contains tables showing the properties of various woods, actual and comparative, with explanations.

43. _____
1954. American woods. U.S. Dep. Agr. [rev. 1953], 4 pp., illus.

Brief discussion of the range, silvical characteristics, supply, wood properties, and uses of Alaska-cedar.

44. Blackerby, Alva W.
1945. Opportunities for minor wood product industries in Alaska. U.S. Forest Serv., Alaska Region, 20 pp., illus.

45. Bones, J. T.
1963. Relating outside- to inside-bark diameter at top of first 16-foot log for southeast Alaska timber. U.S. Forest Serv. North. Forest Exp. Sta. Tech. Note 52, 2 pp.

Shows conversion factors relating diameter outside bark to diameter inside bark for *Tsuga heterophylla*, *Picea sitchensis*, *Chamaecyparis nootkatensis*, and *Thuja plicata*, with information on the number and size of sample trees measured.

46. Bowers, Nathan A.
1942. Cone-bearing trees of the Pacific coast. 169 pp., illus. New York, London: Whittlesey House, div. McGraw-Hill Book Co.

Gives the description, distribution, and some general information about Alaska-cedar.

47. _____
1956. Cone-bearing trees of the Pacific coast. Ed. 5 (rev.), 169 pp., illus. Palo Alto, Calif.: Pacific Books.

48. British Columbia Forest Service.
1957. Continuous forest inventory of British Columbia. 223 pp. Dep. Lands & Forests, Victoria.

49. British Standards Institute.
1955. Nomenclature of commercial timbers including sources of supply. 144 pp. London: Waterlow & Sons, Ltd.

Lists scientific, standard, and common names, sources of supply, and wood properties of many woods, including Alaska-cedar.

50. Britton, N. L., and Shafer, J. A.
1908. North American trees; being descriptions and illustrations of the trees growing independently of cultivation in North America, north of Mexico and the West Indies. 894 pp., illus. New York: Henry Holt & Co.

51. Brockman, C. Frank.
1947. Flora of Mt. Rainier National Park. U.S. Dep. Int., 170 pp., illus.

Alaska-cedar is a conspicuous tree of the Canadian zone between 3,000 and 5,000 feet. Foliage is scalelike, the bark is ash gray and flaky, cones are small and globular, and the branches have a characteristic

drooping appearance as if wilted. This latter character is particularly noticeable along the Paradise Valley highway between Ricksecker Point and Narada Falls.

52. _____
1949. Conifers of the Cascades. Univ. Wash. Arbor. Bull. 12: 11-13, illus.

Just below the subalpine meadow country, the most characteristic tree association is composed of noble fir, Alaska-cedar, and western white pine. Intermingled with these principal species are Douglas-fir and western hemlock.

53. _____
1949. Trees of Mount Rainier National Park. 49 pp., illus. Seattle: Univ. Wash. Press.

Alaska-cedar is a component of the intermediate forest in elevations from 4,000 to 5,200 feet; the subalpine forest, from 5,000 to 6,500 feet; and the timberline forest from 6,500 to 7,000 feet. In the Park, it is found most easily along the Paradise Valley highway in the vicinity of Canyon Rim and Narada Falls. It is a medium-sized tree from 75 to 100 feet tall and from 1-1/2 to 2 (occasionally 3) feet in diameter, but smaller in exposed situations. A general description is given.

54. Brooke, R. C.
1965. The subalpine mountain hemlock zone. Part II. Ecotopes and biogeocoenotic units. In Ecology of western North America. Vol. 1. V. J. Krajina, ed. pp. 79-101. Univ. Brit. Columbia, Dep. Bot.

The subalpine mountain hemlock biogeoclimatic zone occurs on the crests and slopes of innumerable peaks or ridges forming the Coast Ranges and, in the study area which includes part of Garibaldi Park and the North Shore Mountains, it is found at elevations between approximately 3,000 and 5,500 feet. The zone is characterized in detail. Within the forested biogeocoenotic units, Alaska-cedar occurs in association with *Tsuga mertensiana* and *Abies amabilis*. Lesser vegetation is also listed.

55. Brown, H. P., and Panshin, A. J.
1934. Identification of the commercial timbers of the United States. 223 pp., illus. New York, London: McGraw-Hill Book Co.

Describes general characteristics and minute anatomy of many woods. Alaska-cedar has an odor resembling that of raw potatoes, with a faint, bitter, somewhat spicy taste. The wood is comparable to that of *Chamaecyparis lawsoniana*.

56. _____, Panshin, A. J., and Forsaith, C. C.
1949. Textbook of wood technology. Vol. 1, Structure, identification, defects, and uses of the commercial woods of the United States. 652 pp. New York: McGraw-Hill Book Co.

57. Browne, J. E.
1962. Standard cubic-foot volume tables for the commercial tree species of British Columbia, 1962. Brit. Columbia Forest Serv., 107 pp.

Appendices contain standard cubic-foot volume tables and merchantable volume factors for Alaska-cedar.

58. Campbell, R. B., and Robertson, J. Monteath.
1952. The structure of nootkatin; an X-ray determination. Chem. & Ind. Dec. 27: 1266-1267.

59. Canada, Dominion Forest Service.
1961. Native trees of Canada. Can. Dep. Mines & Resources, Dominion Forest Serv. Bull. 61, ed. 6, 291 pp., illus. Ottawa, Ont.: Queen's Printer.

60. Carl, G. Clifford, Guiguet, C. J., and Hardy, George A.
1952. A natural history survey of the Manning Park area, British Columbia. Brit. Columbia Prov. Mus. Occas. Pap. 9, 130 pp., illus.

61. Carlsson, Blenda, Erdtman, H., Frank, A., and Harvey, W. E.
1952. The chemistry of the natural order Cupressales. VIII. Heartwood constituents of *Chamaecyparis nootkatensis*--carvacrol, nootkatin and chamic acid. Acta Chem. Scand. 6(5): 690-696.

A preliminary study of the steam-volatile constituents of the heartwood of *C. nootkatensis* has resulted in the isolation of carvacrol, the "sesquiterpene type" tropolone nootkatin, $C_{15}H_{20}O_2$, and a new acid, $C_{10}H_{14}O_2$, for which the name chamic acid is proposed. (Author's summary.)

62. Chittenden, F. J.
1931. Conifers in cultivation: the report of the conifer conference held by the Royal Horticultural Society. 634 pp., illus. London: Roy. Hort. Soc.

Contains a series of papers which include information on Alaska-cedar grown in Great Britain. Also lists statistics on notably large trees.

63. Clifford, N.
1957. Timber identification for the builder and architect. 141 pp., illus. London: Leonard Hill Ltd.

Describes briefly the color, characteristics, durability, and suitable uses of *Chamaecyparis nootkatensis* wood.

64. Coleman, Babette Brown, Muenscher, Walter C., and Charles, Donald R.
1956. A distributional study of the epiphytic plants of the Olympic Peninsula, Washington. Amer. Midland Natur. 56: 54-87.

The Hudsonian zone from 3,500- to 5,000-foot elevation is characterized by the Alaska-cedar, subalpine fir, mountain hemlock climax. Alaska-cedar is shown to be host to 17 species of lichens and two species of mosses.

65. Coleman, W.
1889. On conifers. J. Roy. Hort. Soc., London, 11: 320-339.

Describes horticultural uses and culture of many conifers, including Alaska-cedar.

66. Collingwood, G. H., and Brush, W. D.
1964. Knowing your trees. Rev. and ed. by Devereux Butcher. 349 pp., illus. Washington, D. C.: American Forestry Association.

67. Coltman-Rogers, Charles.
1920. Conifers and their characteristics. 333 pp., illus. London: John Murray, Albemarle St, W.

68. Cooke, Wm. Bridge.
1962. On the flora of the Cascade Mountains. Wasmann J. Biol. 20(1): 1-67.

69. Cooper, William S.
1942. Vegetation of the Prince William Sound region, Alaska; with a brief excursion into post-Pleistocene climatic history. Ecol. Monogr. 12: 1-22.

The author observed *Chamaecyparis nootkatensis* in the Prince William Sound region at its northwestern limit on Glacier Island, where it is locally abundant and thrifty. A resident fox farmer reported diameters up to 3 feet. The isolated occurrences in Prince William Sound area present an interesting phytogeographic problem, but the species is of no importance ecologically.

70. _____
1957. Vegetation of the Northwest-American province. Pacific Sci. Congr. Proc. 8(4): 133-138.

Alaska-cedar is listed as one of the 12 character trees of the province.

71. Courtot, Y., and Baillaud L.
1955. Sur la repartition des sexes chez un *Chamaecyparis*. (Sex Distribution in a *Chamaecyparis*) Annu. Sci. Univ. Besancon (Ser. 2, Bot.) 6: 75-81.

Examination of a branch of *C. nootkatensis* showed a definite sexual "spectrum," with the apex sterile, the female conelets borne on the intermediate portion of the branch, and the male on the oldest, basal part. (From authors' summary.)

72. Coville, Frederick Vernon, and Funston, Frederick.
1895. Botany of Yakutat Bay, Alaska, with a field report. Contrib. U.S. Nat. Herb. 3(6): 325-353.

One small tree was reported from Khantaak Island near the Indian village.

73. Crosby, David.
1965. Conditions of forest insects in forest regions, Alaska. *In* Forest insect conditions in the United States, 1964. U.S.D.A. Forest Serv., p. 37.

The cedar bark beetle, *Phloeosinus squamosus* Blkm., continued active over much of southeast Alaska, but the rather considerable tree killing was confined to stands of Alaska-cedar of low commercial value.

74. Dallimore, W., and Jackson, A. Bruce.
1923. A handbook of Coniferae including Ginkgoaceae. Ed. 3, 570 pp., illus. London: Edward Arnold & Co.

Includes a general description of the tree and wood, uses, silvical characteristics, list of varieties, and experience with the tree in Great Britain.

75. Davidson, J., and Abercrombie, I.
1927. Conifers, junipers, and yew: gymnosperms of British Columbia. 72 pp., illus. London: T. Fisher Unwin, Ltd.

76. Day, R. J.
1967. A plea for standard tree name abbreviations. Forest. Chron. 43: 121-134.

The author proposes a system for abbreviating tree names in the vernacular. Simple rules are set forth and a list of abbreviations presented. The following is proposed for *Chamaecyparis nootkatensis:* abbreviation--CHn; English vernacular--yellow cypress; French vernacular--Chamaecyparis jaune.

77. Dayton, William A.
1953. Geography of commercially important United States trees. J. Forest. 51: 276-279.

78. Dixon, Dorothy.
1961. These are the champs. Amer. Forests 67(1): 41-50.

The largest Alaska-cedar reported is located in the Olympic National Park, Washington. Circumference at 4-1/2 feet--21 feet; height--175 feet; spread--27 feet 5 inches.

79. Dodwell, Arthur, and Rixon, Theodore F.
1902. Forest conditions in the Olympic Forest Reserve, Washington. U.S. Geol. Surv. Prof. Pap. 7, Ser. H, Forest 4, 110 pp., illus.

Alaska-cedar is found on mountain ridges below 3,500 feet.

80. Doesburg, J. van.
1960. Stekproeven. (Trials with cuttings.) Jaarb. Proefsta. Boomkwek. Boskoop: 29-32. (In Dutch.)

Summarizes results of cutting trials for 1959 and 1960. Two varieties of *Chamaecyparis* were tested; var. *glauca* and var. *pendula*.

81. Downing, G. L.
1960. A cedar bark beetle outbreak, Petersburg Ranger District, North Tongass National Forest, October, 1960. U.S. Forest Serv., Alaska Forest Res. Center, Forest Insect Surv. Rep. 6, 2 pp.

An infestation of western redcedar and Alaska-cedar by *Phloeosinus squamosus* Blkm., a cedar bark beetle, was reported. The outbreak was confined to scrub cedar stands on poorly drained slopes and muskeg bottoms, on Kuiu Island, Alaska.

82. _____
1961. Conditions of forest insects in forest regions, Alaska. *In* Forest insect conditions in the United States, 1960. U.S.D.A. Forest Serv., p. 3.

A cedar bark beetle, *Phloeosinus squamosus* Blkm., was responsible for the death of large numbers of Alaska-cedar and western redcedar on Kuiu and Kupreanof Islands. The outbreak extends over several thousand acres and is confined primarily to scrub cedar stands.

83. Duff, S. R., and Erdtman, H.
1954. The chemistry of the natural order of Cupressales. X. Nootkatin. Chem. & Ind. 15: 432-433.

Presents chemical proof for the structure deduced from X-ray evidence for the tropolone nootkatin, $C_{15}H_{20}O_2$, from the heartwood of *Chamaecyparis nootkatensis*.

84. _____, Erdtman, H., and Harvey, W. E.
1954. The chemistry of the natural order Cupressales. XII. Heartwood constitutents of *Chamaecyparis nootkatensis* (Lamb.) Spach. Nootkatin. Acta Chem. Scand. 8(6): 1073-1082.

85. Dunn, Malcolm.
1892. The value in the British Islands of introduced conifers. J. Roy. Hort. Soc., London 14: 73-102.

Cupressus nootkatensis, or as it is perhaps better known, *Thuyopsis borealis*, is one of the hardiest and most beautiful of the cypresses, and appears to thrive everywhere in the British Isles. It is somewhat branchy for a timber tree, but when planted close, it forms a clean straight stem. The tallest tree recorded in Britain is at Murthyly: 50 feet high and 1 foot 9 inches girth. Dimensions of several other large trees are given.

86. Eades, H. W.
1932. British Columbia softwoods, their decays, and natural defects. Can. Dep. Int., Forest Serv. Bull. 80, 126 pp., illus.

87. Earl, Derek.
1958. Yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach). Quart. J. Forest. 52(3): 204-207 plus 1 plate.

Discusses the silvics of Alaska-cedar in its natural range, particularly in British Columbia, with notes on its timber characteristics, and the history of the species in Britain.

88. Ebell, L. F., and Schmidt, R. L.
1964. Meteorological factors affecting conifer pollen dispersal on Vancouver Island. Can. Dep. Forest., Forest Res. Br. Pub. 1036, 28 pp., illus.

89. Ebell, Lorne F., and Schmidt, Ralph L.
1960. Effect of elevation and climatic factors on production and dispersal of coniferous-tree pollen. (Abstr.) Soc. Amer. Forest. Proc. 1959: 39.

In a test of daily and seasonal flowering during 1958 and 1959 on Vancouver Island, the following order of flowering among conifers was observed: *Tsuga heterophylla, Chamaecyparis nootkatensis, Pseudotsuga menziesii, Abies grandis, A. amabilis, Pinus contorta, P. monticola, A. lasiocarpa,* and *T. mertensiana.* Flowering began later with increasing elevation, but pollen production did not decrease with elevation.

90. Edlin, Herbert L.
1964. A modern "Sylva" or "A discourse of forest trees." Cypresses: conifers of the *Cupressus* and *Chamaecyparis* genera. Quart. J. Forest. 58(3): 208-217.

Nootka cypress appears well suited for growth in the colder districts of Great Britain, although it is little used as a plantation tree, possibly because of its slow rate of growth. This is a common feature of all trees from the Far North. The tree is described briefly. The intergeneric hybrid, Leyland cypress, is mentioned briefly. The largest tree at Leighton Hall, planted in 1911, is 82 feet tall and 8-1/2 feet in girth.

91. Eis, Slavoj.
1962. Statistical analysis of several methods for estimation of forest habitats and tree growth near Vancouver, B.C. Univ. Brit. Columbia Fac. Forest. Forest. Bull. 4, 76 pp., illus.

92. Eliot, Willard Ayres, and McLean, G. B.
1948. Forest trees of the Pacific coast. New ed., 565 pp., illus. New York: G. P. Putnam's Sons.

93. Enari, Leonid.
1956. Plants of the Pacific Northwest. 315 pp., illus. Portland, Oregon: Binfords & Mort.

94. England, R. F., and Stahl, E.
1963. Marine laminating properties of selected wood species: outdoor exposure--Alaska-cedar (*Chamaecyparis nootkatensis*), western larch (*Larix occidentalis*). Bureau Ships Index No. SR007-03-02, Ident. No. 37-1004-2, Prog. Rep. E-412-L3. Puget Sound Naval Shipyard, Bremerton, Wash. 5 pp.

Wood laminates of Alaska-cedar and western larch, adhesive bonded with three commercial phenol resorcinol formaldehyde adhesives, were exposure tested. Based on 18 months' outdoor exposure, it is concluded that laminates of Alaska-cedar and western larch made according to described specifications should be satisfactory for marine service use.

95. English, Edith Hardin.
1951. The flowering season on Mount Baker. Univ. Wash. Arboretum Bull. 14(3): 8-12.

Alaska-cedar occurs only occasionally on Mount Baker, associated with mountain hemlock and subalpine fir.

96. Erdtman, H.
1952. Chemistry of some heartwood constituents of conifers and their physiological and taxonomic significance. *In* Progress in organic chemistry, 1. J. W. Cook, ed., pp. 22-63. London: Butterworths Sci. Publ.

Alaska-cedar heartwood was found to contain at least one new tropolone derivative called nootkatin. The wood also contains carvacrol LII, a terpenoid phenol, formerly known among conifers only in the genus *Tetraclinis*.

97. _____ and Harvey W. E.
1952. The chemistry of the natural order Cupressales. IX. Nootkatin. Chem. & Ind. 71(52): 1267.

98. _____, Harvey, W. E., and Topliss, J. G.
1956. The chemistry of the natural order Cupressales. XVI. Heartwood constituents of *Chamaecyparis nootkatensis* (Lamb.) Spach. The structure of chamic and chaminic acids. Acta Chem. Scand. 10(9): 1381-1392.

Describes the structure of chamic and chaminic acids, derived from the heartwood of Alaska-cedar. Chaminic acid has been shown to be the optical antipode of isochamic acid.

99. _____ and Topliss, J. G.
1957. The chemistry of the natural order Cupressales. XVIII. Nootkatene, a new sesquiterpene type hydrocarbon from the heartwood of *Chamaecyparis nootkatensis* (Lamb.) Spach. Acta Chem. Scand. 11(7): 1157-1161.

A preliminary study of the neutral constituents gave terpenoid hydrocarbons, alcohols, compounds containing carbonyl, and carvocrol methyl ether. Nootkatene was isolated in an apparently pure state. (From author's summary.)

100. Erdtman, Holger, and Hirose, Yoshiyuki.
1962. The chemistry of the natural order Cupressales. 46. The structure of nootkatone. Acta Chem. Scand. 16(6): 1311-1314.

Nootkatone, a new eudalenoid sesquiterpene ketone, was isolated from heartwood of *Chamaecyparis nootkatensis*.

101. Fitzpatric, H. M.
1965. Conifers: keys to the genera and species, with economic notes. Roy. Dublin Soc. Sci. Proc. 2(7): 67-129 plus 10 plates.

Presents a comprehensive description of the conifers, based on foliage morphology, in the form of an artificial key. Eighteen species of *Cupressus* and *Chamaecyparis* are listed, including Alaska-cedar.

102. Fonda, R. W.
1966. Ecology of montane and subalpine forests in Olympic National Park. Ecol. Soc. Amer. Bull. 47(3): 140.

103. Forest Products Laboratories Division (Canada).
1951. Canadian woods; their properties and uses. Ed.2, 367 pp., illus. Ottawa: King's Printer.

Tabulations of physical and mechanical properties are included in the appendix.

104. Forest Products Research (London).
1957. A handbook of softwoods. Dep. Sci., Ind. Res., 73 pp. London: Stationery Off.

105. Fowells, H. A.
1965. Silvics of forest trees of the United States. U.S. Dep. Agr. Handb. 271, 762 pp., illus.

Contains a revision of silvical characteristics of Alaska-cedar (Andersen, H. E., 1959).

106. Franklin, Jerry F.
1961. A guide to seedling identification for 25 conifers of the Pacific Northwest. U.S. Forest Serv. Pacific Northwest Forest & Range Exp. Sta., 65 pp., illus.

An illustrated key to seedling identification. *Chamaecyparis nootkatensis* seedlings have two (rarely three) cotyledons, flat in cross section, less than 12 mm. long; juvenile needles not glaucous.

107. _____
1965. Tentative ecological provinces within the true fir-hemlock forest areas of the Pacific Northwest. Pacific Northwest Forest & Range Exp. Sta., U.S.D.A. Forest Serv. Res. Pap. PNW-22, 31 pp., illus.

108. _____ and Mitchell, Russel G.
1967. Successional status of subalpine fir in the Cascade Range. Pacific Northwest Forest & Range Exp. Sta., U.S.D.A. Forest Serv. Res. Pap. PNW-46, 16 pp., illus.

109. _____ and Trappe, James M.
1963. Plant communities of the northern Cascade Range: a reconnaissance. Northwest Sci. 37: 163-164.

Alaska-cedar may be a component of avalanche communities maintained as topographic climaxes.

110. Frost, F.
1951. Forsok med sneskjermplantninger pa Saltjellet. (Investigations on planting snowbreaks on Saltfjell) Tidsskr. Skogbr. 59(6): 176-185. (In Norwegian.)

Discusses the planting of snowbreaks along the railroad across Saltfjell, north of the Arctic Circle, reaching an altitude of 680 m.

111. Garman, E. H.
1953. Pocket guide to the trees and shrubs of British Columbia. Ed. 2, Brit. Columbia Forest Serv. Bull. 28, 102 pp., illus.

112. Gass, Charles R., Billings, Richard F., Stephens, Freeman R., and others.
1967. Soil management report for the Hollis area. U.S. Forest Serv., Tongass National Forest, Alaska Region. 118 pp., illus.

Describes soils and vegetation on a portion of Prince of Wales Island, Alaska. Alaska-cedar occurs from sea level to about 1,500 feet, and occurs on the following soils series: Maybeso, McGilvery, St. Nicholas, and Wadleigh.

113. Gorman, M. W.
1907. Vegetation of the northeast slope of Mount Baker. Mazama 3(1): 31-48.

Alaska-cedar was seen above 4,000 feet, but was observed only about Slate Mountain. Only small trees were seen, some of these bearing fertile cones. Dead trees, up to 20 inches in diameter, were remnants of a stand previously destroyed by fire.

114. _____
1920. The flora of Mount Hood. Oreg. Out-of-Doors 1(1): 64-96.

Alaska-cedar, formerly thought to reach its southern limit here, is now known to be fairly common on Mount Jefferson and Whiskey Peak (Josephine County) 3 miles from the California border. On Mount Hood, Alaska-cedar is found on moist slopes on the south and west sides up to 4,000 feet.

115. Gorman, Martin W.
1899. Eastern part of Washington Forest Reserve. U.S. Geol. Surv. 19th Annu. Rep., 1897-98, Part 5, Forest Reserves: 315-350, illus.

Within the region described, Alaska-cedar is found only in moist ravines or canyons that head in or about the main divide of the Cascade Range. Its altitudinal range is from 2,100 feet on the Stehekin to 6,000 feet about the headwaters of the Methow River and Rattlesnake Creek. Finest specimens range from 50 to 75 feet in height and 10 to 25 inches in diameter. At its upper limits the tree is stunted, with an alpine appearance.

116. _____
1929. New stations for trees in Oregon. Madrono 1: 275.

The author collected a specimen of Alaska-cedar from Whiskey Peak, Josephine County, Oregon, 3 miles from the California border.

117. Grant, John A., and Grant, Carol L.
1943. Trees and shrubs for Pacific Northwest gardens. 335 pp., illus. Seattle: Frank McCaffrey, Dogwood Press.

118. Greaves, C., and Schwartz, H.
1951. The chemical utilization of wood. *In* Canadian woods; their properties and uses. Ed. 2, pp. 209-234, illus. Ottawa: King's Printer.

Analysis of wood is tabulated (mean values obtained in percentage of ovendry wood).

119. Green, George Rex.
1933. Trees of North America (exclusive of Mexico). Vol. 1, The conifers. 186 pp. Ann Arbor: Edward Bros., Inc.

A concise description of Alaska-cedar, including silvics, morphology, and uses.

120. Greguss, Pál.
1955. Identification of living gymnosperms on the basis of xylotomy. Akadémiai Kiadó, Budapest. 263 pp. (plus 350 plates & 8 summary key sheets in pocket). (In German.)

Provides anatomical key and illustration of Alaska-cedar.

121. Greig, E. J.
1964. Some notes on the mountain flora of Vancouver Island. Univ. Wash. Arboretum Bull. 27: 98-99, 112-113.

Alaska-cedar is a component of the Hudsonian zone near timberline at 5,000 feet and one of the dominant trees where the transition zone merges into the Canadian zone at 4,000 feet.

122. Gripenberg, Jarl.
1953. The constituents of the heartwood of the genus *Thuja* and some related genera. J. Sci. Ind. Res., India 12A(5): 233-237.

Reviews information on the constituents of *Thuja plicat l'. occidentalis, Chamaecyparis obtusa, C. nootkatensis* and *Thujopsis dolabrata.*

123. Guiguet, C. J.
1953. An ecological study of Goose Island, British Columbia, with special reference to mammals and birds. Brit. Columbia Provisional Mus. Occas. Pap. 10, 78 pp., illus.

On Goose Island, two plant associations are included in the general heading of coniferous forest; the typical coast climax association of western redcedar, western hemlock, and Sitka spruce, and an association which includes western redcedar, western hemlock in association with lodgepole pine, Alaska-cedar, and Pacific yew. The latter is a stunted forest forming an ecotone between spruce, hemlock, and muskeg associations, and also predominates in rocky areas. Floral composition is described by the Aldous method.

124. Hagem, Oscar.
1931. Forsok med Vestamerikanske Traeslag. (Studies on Western American tree species.) Medd. Forstl. Forsokssta. 12. 4(2): 1-127 plus 4 maps.

Describes Alaska-cedar provenance trials in Norway from Alaska, British Columbia, Washington, and California.

125. Hale, J. D.
1951. The structure of wood. *In* Canadian woods; their properties and uses. Ed. 2, pp. 57-104, illus. Ottawa: King's Printer.

Contains a key to the identification of woods commonly used in Canada.

126. Halliday, W. E. D.
1937. A forest classification for Canada. Dep. Mines, Resources, Can. Forest Serv. Bull. 89, 50 pp. plus map.

Alaska-cedar is a component of the coast forest region. Amabilis fir and Alaska-cedar occur generally, their ability to stand drier conditions being shown by their presence toward the upper limits of tree growth.

127. Hanan, A. M. S.
1967. Species trials and silvicultural control of mixed species. Dep. Lands, Ireland. Forest Div. Forest Res. Rev. 1957/64: 43-59.

Describes trials of *Cupressocyparis leylandii*, which so far has proved to be a vigorous, reasonably hardy tree.

128. Hansen, Carl.
1892. Pinetum Danicum. Conifers collected and observed by Professor Carl Hansen, Mynstersvei 2, Copenhagen V. J. Roy. Hort. Soc. 14: 257-480.

"Mr. Menzies was the first discoverer of this species. He obtained specimens from Nootka Sound, when Vancouver (with whom he sailed as surgeon and naturalist) stopped there in his celebrated voyage round the world; and from his specimens Lambert described it in his "Genus Pinus." It was introduced from the Botanic Garden of St. Petersburg into Europe, under the name of *Thuyopsis borealis*, about 1850, and is now plentifully distributed. Mr. R. Brown, who collected for the Edinburg "British Columbia Botanical Association" in one of his letters . . . says "Next morning looking about our neighborhood, we re-entered our canoe, hollowed out of *Cupressus nutkaensis*, the mats we sat upon being made of the fibre of the same tree, ropes of the same material, and occasionally of *Thuya plicata.*" Notes on habits and habitat are given. The tree was introduced in Denmark in 1870.

129. Hansen, Henry P.
1950. Pollen analysis of three bogs on Vancouver Island, Canada. J. Ecol. 38: 270-276.

130. Hanzlik, E. J.
1925. A site classification scheme for the western Cascades forest region. Univ. Wash. Forest. Club Quart. 4(1): 5-8.

Alaska-cedar is a component of sites IV and V. Generally these sites are from 2,500 feet to 4,500 feet in northern Washington and from 3,500 to 4,000 feet in Oregon. Site IV associates are western hemlock, Pacific silver fir, noble fir, and mountain hemlock. Site V associates are Pacific silver fir, mountain hemlock, and subalpine fir.

131. Hanzlik, Edward John.
1928. Trees and forests of western United States. 128 pp. Portland, Oregon: Dunham Printing Co.

132. Hard, J. S.
1967. Identification of destructive Alaska forest insects. U.S.D.A. Forest Serv., Pacific Northwest Forest & Range Exp. Sta., 19 pp., illus.

133. Harlow, William M., and Harrar, Elwood S.
1950. Textbook of dendrology. Ed. 3, 555 pp., illus. New York: McGraw-Hill Book Co.

134. Harrar, E. S.
1957. Hough's encyclopaedia of American woods. 204 pp., illus. New York: Robert Speller & Sons.

Briefly describes the discovery, uses, habits, and morphology of the tree, diagnostic features of the wood, and its microscopic anatomical features. Physical and mechanical properties are tabulated.

135. Harris, A. S.
1962. Cone crops in coastal Alaska--1960 and 1961. U.S.D.A. Forest Serv. North. Forest Exp. Sta. Tech. Note 53, 4 pp.

A report for Alaska-cedar indicated a "medium" crop of both 1- and 2-year cones near Petersburg (Alaska). The only report from the Sitka District showed a crop failure.

136. Hazard, John W.
1963. Forest statistics for Chelan and Douglas counties, Washington, 1959-60. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Resource Bull. PNW-5, 26 pp.

Forest statistics for Chelan and Douglas Counties are given as of 1959-60. On commercial forest land, the volume of Alaska-cedar growing stock 5.0 inches d.b.h. and larger was 3 million cubic feet. Volume of Alaska-cedar sawtimber 11.0 inches d.b.h. and larger was 10 million board feet (Scribner).

137. _____
1965. Timber resource statistics for southwest Washington. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Resource Bull. PNW-15, 32 pp.

Forest statistics for southwest Washington, which includes Clark, Cowlitz, Lewis, Pacific, Skamania, and Wahkiakum counties, are given as of January 1, 1964. On commercial forest land, the volume of Alaska-cedar growing stock 5.0 inches d.b.h. and larger was 24 million cubic feet. Volume of Alaska-cedar sawtimber 11.0 inches d.b.h. and larger was 120 million board feet (Scribner).

138. _____ and Metcalf, Melvin E.
1965. Forest statistics for west central Oregon. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Resource Bull. PNW-10, 35 pp.

Forest statistics for west-central Oregon, which includes Benton, Lane, Lincoln, and Linn Counties, are given as of 1963. On commercial forest land, the volume of Alaska-cedar growing stock 5.0 inches d.b.h. and larger was 3 million cubic feet. Volume of Alaska-cedar sawtimber 11.0 inches d.b.h. and larger was 7 million board feet (Scribner).

139. Hegnauer, R.
1962. Chemotaxonomie der Pflanzen. Eine Ubersicht uber die Verbreitung und die systematische Bedeutung der Pflanzenstoffe. (Chemotaxonomy of plants. A survey of the distribution and systematic significance of plant constituents.) Thallophytes, Bryophytes, Pteridophytes and Gymnosperms. Vol. I. 517 pp. illus. Birkhauser Verlag: Basel-Stuttgart. (In German.)

140. Henry, J. K.
1915. Flora of southern British Columbia and Vancouver Island: with many references to Alaska and northern species. 363 pp. Toronto: W. J. Gage & Co., Ltd.

141. Heusser, C. J.
1960. Late-Pleistocene environments of north Pacific North America. Amer. Geogr. Soc., Spec. Pub. 35, 308 pp., illus.

Describes the distribution, habitat, and plant associates of Alaska-cedar throughout its range.

142. Heusser, Calvin J.
1964. Palynology of four bog sections from the western Olympic Peninsula, Washington. Ecology 45: 23-40, illus.

143. _____
1965. A Pleistocene phytogeographical sketch of the Pacific Northwest and Alaska. *In* The quaternary of the United States. H. E. Wright, Jr., and David G. Frey, eds. pp. 469-483, illus. Princeton, N. J.: Princeton Univ. Press.

144. Hibberson, R. W.
1921. Yellow cedar in British Columbia. The Timberman 22(12): 138.

A brief description of Alaska-cedar in British Columbia.

145. Higinbotham, N., and Higinbotham, Betty Wilson.
1954. Quantitative relationships of terrestrial mosses with some coniferous forest at Mount Rainier National Park. Butler Univ. Bot. Stud. 11: 149-168.

Characterizes the terrestrial plant communities of typical climax stands. Above the *Abies amabilis-Tsuga mertensiana* forest, *T. mertensiana* and *C. nootkatensis* assume dominance, generally at elevations between 4,000 to 5,000 feet. The plant community is described.

146. Hiorth, G.
1956. Allverdens traer i norsk jord. (Trees of the world on Norwegian soil.) 245 pp. S. Bern. Hegland-Flekkefjord: Tryktog Bundet Hos. (In Norwegian.)

147. Hoffman, B. E.
1913. Alaska woods, their present and prospective uses. Forest Quart. 11(2): 185-200.

Uses and characteristics of Alaska-cedar.

148. Holubcik, M.
1960. Prispevok kotazke pestovania cudzokrajnych drevin v nasich porastoch. (Raising exotics in Czechoslovak stands) Lesn. Cas. 6(1): 64-75 (In Slovak.)

Discusses briefly experience with and possibilities for 14 conifers including *Chamaecyparis nootkatensis* and a few broad-leaved species.

149. Howell, Thomas.
1903. A flora of Northwest America. Vol. 1, Phanerogamae. 792 pp. Portland, Oregon.

150. Hulten, E.
1937. Outline of the history of arctic and boreal biota during the Quaternary period; their evolution during and after the Glacial period as indicated by the equiformal progressive areas of present plant species. 168 pp. plus 43 plates. Stockholm: Bokforlags Aktiebolaget Thule.

151. _____
1941. Flora of Alaska and Yukon I. Botanical Museum, Lunds Univ. Arsskr., N. F., Avd. 2, 37(1): 1-127.

152. Huntington, LeRoy W.
1923. Forest aspects of Alaska. Univ. Wash. Forest Club Quart. 1(4): 15-26.

Describes forest conditions in Alaska. Minimum stumpage rate for Alaska-cedar on the Tongass Forest is $1.50 per thousand board feet. A few Alaska-cedar logs have been shipped to Japan but receipts did not justify continuing export.

153. Hutchinson, Ian.
1958. Some aspects of logging in the coast forest of British Columbia. I. Empire Forest. Rev. 37(1): 66-84.

As of 1955, the inventory of mature Alaska-cedar in mature stands was 1,560,123 cubic feet. Annual cut of Alaska-cedar for all timber products was 3,336 cubic feet.

154. Hutchison, O. Keith.
1967. Alaska's forest resource. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Resource Bull. PNW-119, 74 pp., illus.

In Alaska the volume of Alaska-cedar and western redcedar is about 4 billion board feet each. There is no active market for either species today. A photo of a tree 4 feet in diameter is shown on page 46.

155. Institute of Forest Products.
1957. Conversion factors for Pacific Northwest forest products. Univ. Wash. Dep. Conserv., 28 pp.

156. Jackson, A. Bruce, and Dallimore, W.
1926. A new hybrid conifer. Roy. Bot. Gardens, Misc. Inform. Bull. Kew. 3: 113-115.

Describes the occurrence of a chance hybrid between yellow cedar and Monterey cypress. Authors propose to name it *Cupressus leylandii*.

157. Jaeger, Edmund C.
1962. A source book of biological names and terms. Ed. 3, 323 pp., illus. Springfield, Ill: Charles C. Thomas.

Chamae- (Greek) in botany sometimes signifies false.

Cyparis- (Greek) Kyparissos means cypress. Hence, the generic name *Chamaecyparis*, or false cypress.

158. Jepson, W. L.
1910. The silva of California. Vol. 2. 480 pp., illus. Berkeley:. Calif. Univ. Mem.

159. Jepson, Willis Linn.
1933. Phytogeography of the coniferae of western North America. Fifth Pacific Sci. Congr. Proc., pp. 3255-3264.

160. Jones, George Neville.
1936. A botanical survey of the Olympic Peninsula, Washington. Univ. Wash. Biol. Pub. 5, 286 pp., illus.

161. _____
1938. The flowering plants and ferns of Mount Rainier. Univ. Wash. Biol. Pub. 7, 192 pp., 9 plates.

162. Kelsey, Harlan P., and Dayton, William A.
1942. Standardized plant names. Ed. 2 (rev. and enl.), 675 pp. Harrisburg, Pa.: McFarland Co.

Approved common name is nootka falsecypress. The following clons are recognized: blue (*glauca*), compact (*compacta*), Sanders (*sanderi*), silver (*argenteovariegata*), weeping (*pendula*), and yellow leaf (*lutea*).

163. Kennedy, Elma I.
1965. Strength and related properties of woods grown in Canada. Can. Forest Prod. Res. Br. Dep. Forest. Pub. 1103, 51 pp.

164. Klein, David R.
1965. Ecology of deer range in Alaska. Ecol. Monogr. 35: 259-284.

On both Woronkofski and Coronation Islands, Alaska, Alaska-cedar is often present as a subordinant tree in the overmature stands; but in blowdown areas and muskeg edges on Coronation Island and in an old burn on Woronkofski Island, it is frequently a dominant species or codominant with hemlock and spruce. In open scrub forests on poorly drained sites, lodgepole pine is usually the dominant tree form although it is frequently replaced by Alaska-cedar on Coronation Island. Trees are dwarfed, commonly not over 20-30 feet in height, and widely spaced.

165. Koehler, A.
1949. Key for identification of woods without the aid of a hand lens or microscope. U.S. Dep. Agr. Yearbook 1949: 833-839.

166. Krajina, V. J. (ed.)
1963. 1962 progress report National Research Council grant No. T-92. Ecology of the forests of the Pacific Northwest. Univ. Brit. Columbia, Dep. Biol. & Bot., 105 pp.

167. _____
1964. 1963 progress report National Research Council grant No. T-92. Ecology of the forests of the Pacific Northwest. Univ. Brit. Columbia, Dep. Biol. & Bot., 94 pp.

168. _____
1965. Ecology of western North America. Vol. 1. Univ. Brit. Columbia, Dep. Bot., 112 pp.

169. _____
1965. 1964 progress report National Research Council grant No. T-92. Ecology of the Pacific Northwest and of western Canadian arctic and subarctic. Univ. Brit. Columbia, Dep. Biol. & Bot. 18 pp.

170. _____
1965. Biogeoclimatic zones and classification of British Columbia. *In* Ecology of western North America. Vol. 1. Univ. Brit. Columbia, Dep. Bot., pp. 1-17.

Coniferous trees growing in the Pacific Northwest are listed by lower and subalpine altitudes according to their increasing shade tolerance. In subalpine altitudes, *Chamaecyparis nootkatensis*, along with *Tsuga mertensiana* and *Abies amabilis*, are listed in seventh and last place, being most shade tolerant. British Columbia is divided into seven biogeoclimatic regions (formations) and several zones. Alaska-cedar is one of the plant indicator species present in the Pacific coastal subalpine forest region in the mountain hemlock zone.

171. _____
1966. 1966 progress report National Research Council grant No. A-92. Ecology of the Pacific Northwest and of western Canadian arctic and subarctic. Univ. Brit. Columbia, Dep. Bot., 41 pp.

172. Krajina, Vladimir J.
1959. Bioclimatic zones in British Columbia. Univ. Brit. Columbia Bot. Ser. 1, 47 pp.

173. Krause, A.
1956. The Tlingit Indians: Results of a trip to the northwest coast of America and Bering Straits. (Trans. by E. Gunther) 272 pp., illus. Seattle: Univ. Wash. Press. (Originally published as, Die Tlinkit-Indianer, Jena, 1885.)

Alaska-cedar, found singly near Sitka, has a splendid wood for carving. The strong, aromatic odor is supposed to be protection against moths and other harmful insects. For this quality, it was highly prized in China where it was formerly imported and made into trunks under the name of camphor wood by the Chinese. The ship worm, the teredo, is supposed to not touch cedar. Uses of the tree by the Tlingit Indians are also described.

174. Kriz, Zdenek.
1960. Rod *Thuja* L. a *Chamaecyparis* Spach v Krajskem arboretu v Novem Dvore u Opavy. (The genera *Thuja* and *Chamaecyparis* in the Novem Dvore arboretum near Opava.) Acta Dendrologica Cechoslovaca, Opava No. 2, 1959/60: 253, 267-269. (In Slovak.)

Notes on 16 forms of *Thuja* and 18 species and forms of *Chamaecyparis*.

175. Kurth, E. F.
1950. The chemical analysis of western woods. Part III. TAPPI 33(10): 507-508.

Four species of western hardwoods and four species of western softwoods, including *Chamaecyparis nootkatensis*, were analyzed for ether, alcohol, water extractives, holocellulose, lignin, methoxyl group, acetyl group, and ash content.

176. Langille, H. D., Plummer, Fred G., Dodwell, Arthur, Rixon, Theodore F., and others.
1903. Forest conditions in the Cascade Range Forest Reserve, Oregon. U.S. Geol. Surv. Prof. Pap. 9, Ser. H, Forest. 6. 298 pp., illus.

Forest conditions in the Cascade Range Forest Reserve are described by township. Alaska-cedar was found in 14 townships within the reserve, but only in two were the trees large and numerous enough to be included in timber estimates. Mature trees are 1.5 feet in diameter and 45 feet high, with 12 feet of clear trunk.

177. Liddicoet, A. R., and Righter, F. I.
1960. Trees of the Eddy Arboretum. U.S.D.A. Forest Serv., Pacific Southwest Forest & Range Exp. Sta. Misc. Pap. 43, 41 pp., illus.

178. Little, Elbert L., Jr.
1949. To know the trees; important forest trees of the United States. U.S. Dep. Agr. Yearbook 1949: 763-814.

179. _____
1953. Check list of native and naturalized trees of the United States (including Alaska). U.S. Dep. Agr. Handb. 41, 472 pp.

180. Lucas, Colin Cameron.
1926. The essential oil content of the *Chamaecyparis nootkatensis*. Master's thesis, Univ. Brit. Columbia, 49 pp.

181. Lyons, C. P.
1956. Trees, shrubs and flowers to know in Washington. 211 pp., illus. Toronto, Vancouver: J. M. Dent & Sons, Ltd.

182. MacDonald, J.
1952. The place of northwestern American conifers in British forestry. Forest. Comm., London. 21 pp. (6th Brit. Commonwealth Forest. Conf., Can. 1952).

Alaska-cedar has not been planted extensively as a forest tree in Britain, because its growth is slow and it often forks very badly. However, it hybridizes with *Cupressus macrocarpa*, to produce *Cupressocyparis leylandii*. This hybrid is apparently more frost resistant than either of its parents and shows remarkable vigor.

183. MacDonald, James, Wood, R. F., Edwards, M. V., and Aldhous, J. R.
1957. Exotic forest trees in Great Britain. Brit. Forest. Comm. Bull. 30, 167 pp., illus.

The Nootka cypress, discovered by Archibald Menzies in 1793 and introduced into Great Britain in 1853, has been planted as a specimen tree and ornamental in most parts of Britain and has succeeded. A number of examples are given. The tree does not seem to be greatly affected by late spring frosts and is able to withstand exposure. However, it is slow growing and is damaged by deer. The seeds require stratification for up to a year before sowing.

184. MacMillan, Bloedel, and Powell River Limited.
[n. d.] Characteristics and uses of yellow cedar. 9 pp. plus tables. Vancouver, Brit. Columbia

185. Markwardt, L. J.
1930. Comparative strength properties of woods grown in the United States. U.S. Dep. Agr. Tech. Bull. 158, 38 pp.

Tables include data on specific gravity, shrinkage, and composite strength values of many hardwoods and softwoods, including Alaska-cedar.

186. _____
1930. Aircraft woods: their properties, selection, and characteristics. U.S.D.A. Forest Serv., Forest Prod. Lab., Nat. Adv. Comm. Aeron. Rep. 354, 34 pp.

Strength of various woods for aircraft design is given, and factors affecting these values are discussed. Alaska-cedar may be considered with red, white, and Sitka spruce for use in highly stressed parts, such as wing beams.

187. _____
1931. The distribution and the mechanical properties of Alaska woods. U.S. Dep. Agr. Tech. Bull. 226, 80 pp., illus.

Gives information of the range, distribution, supply, properties, and uses of Alaska-cedar, and a general description of the tree. The total stand is estimated to be about 10 billion board feet, with about 2.5 billion board feet in Alaska.

188. _____
1941. Aircraft woods: Their properties, selection, and characteristics. U.S. Dep. Agr. Forest Prod. Lab. Rep. 1079, 51 pp. (Reprint, Nat. Adv. Comm. Aeron. Rep. 354.)

Describes the important characteristics of many woods for aircraft construction, including Alaska-cedar. Alaska-cedar is not likely to be considered for use in aircraft because of its limited supply. It may serve as a species supplementary to spruce in some applications, the result being somewhat greater strength at the expense of increased weight.

189. _____ and Wilson, T. R. C.
1935. Strength and related properties of woods grown in the United States. U.S. Dep. Agr. Tech. Bull. 479, 99 pp.

Lists mechanical properties of Alaska-cedar.

190. Mason, Herbert L.
1941. The Alaska-cedar in California. Madrono 6: 90-91.

Alaska-cedar was collected in 1939 on the northeast slope of Mount Emily in northwestern Siskiyou County, and was reported seen on Little Grayback, farther to the west. Both localities are a little over 2 miles from the Oregon border. Specimens of the Mount Emily material are deposited in the herbarium at Rancho Santa Ana Botanic Garden, Anaheim, California. Trees associated with Alaska-cedar were *Abies shastensis*, *Picea breweriana*, *Pinus monticola*, *Libocedrus decurrens*, and *Taxus brevifolia*.

191. Mayr, Heinrich.
1890. Die Waldungen von Nordamerika ihre Holzarten, deren Anbaufahigkeit und forstlicher Werth fur Europa im Allgemeinen und Deutschland insbensonder. (The forests of North America, their tree species, their cultivation possibilities, and general forest values for Europe.) 448 pp., illus. Munchen: University Buchhandlung. (In German.)

192. McAvoy, Blanche.
1931. Ecological survey of the Bella Coola region. Bot. Gaz. 92: 141-171.

Alaska-cedar was found at only one location in the region (on a mountain along the north border at the west end of the valley).

193. McElhanney, T. A.
1951. Commercial timbers of Canada. *In* Canadian woods; their properties and uses. pp. 23-56. Ottawa: King's Printer.

194. McGugan, B. M.
1958. Forest lepidoptera of Canada, recorded by the forest insect survey. Vol. 1, Papilionidae to Arctiidae. Can. Dep. Agr., Forest Biol. Div. Pub. 1034, 76 pp., illus.

195. McMinn, Howard E., and Maino, Evelyn.
1951. An illustrated manual of Pacific coast trees. 409 pp., illus. Berkeley, Los Angeles: Univ. Press.

196. Mertie, J. B.
1931. Notes on the geography and geology of Lituya Bay, Alaska. U.S. Geol. Surv. Bull. 836-B: 117-135.

Alaska-cedar averaging 3 feet in diameter is reported growing on benches.

197. Metcalf, Melvin E., and Hazard, John W.
1964. Forest statistics for northwest Oregon. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Resource Bull. PNW-7, 38 pp.

Forest statistics are given for the following counties: Clackamas, Clatsop, Columbia, Hood River, Marion, Multnomah, Polk, Tillamook, Washington, and Yamhill. On commercial forest land, the volume of Alaska-cedar growing stock 5.0 inches d.b.h. and larger was 5 million cubic feet. Volume of Alaska-cedar sawtimber 11.0 inches d.b.h. and larger was 10 million board feet (Scribner).

198. Molnar, A. C., Harris, J. W. E., and Ross, D. A.
1965. British Columbia region. Can. Dep. Forest., Forest Insect Dis. Surv., pp. 93-109, illus. Ottawa.

199. Morton, B. R., and Lewis, R. G.
1917. Native trees of Canada. Can. Dep. Int. Forest. Br. Bull. 61, 233 pp., illus.

Gives range and description of Alaska-cedar in Canada.

200. Muenscher, W. C.
1941. The flora of Whatcom County, State of Washington; vascular plants. 139 pp. Ithaca, New York: William A. Church Co.

A catalog of plant collections made by the author. Lists seven locations where specimens of Alaska-cedar were collected. In Whatcom County, Alaska-cedar is locally common in cool, moist mountain valleys, sometimes forming clumps of trees in alpine meadows.

201. Muir, John.
1915. Travels in Alaska. 327 pp., illus. Boston and New York: Houghton Mifflin Co.

202. Mulholland, F. D.
1937. The forest resources of British Columbia. Dep. Lands, B.C. Forest Serv., 153 pp., illus. Victoria.

Total merchantable timber and accessible merchantable timber by forest district is given. Alaska-cedar volume is shown in the Vancouver and Prince Rupert district. Total merchantable volume is 3,019,200,000 board feet, of which 1,398,300,000 board feet is accessible.

203. Munday, Don.
1931. Ancients of the sky lines. Can. Forest. & Outdoors 27(11): 25-27, illus.

A general discourse on Alaska-cedar, its appearance, habitat, growth rate, stature, and longevity. The largest trees seen by the writer were 19-1/2 and 20-1/2 feet in circumference and were estimated to be at least 3,500 years old.

204. Munns, E. N.
1938. The distribution of important forest trees of the United States. U.S. Dep. Agr. Misc. Pub. 287, 176 pp., illus.

Contains a range map of Alaska-cedar on page 60.

205. Newlin, J. A., and Wilson, Thomas R. C.
1917. Mechanical properties of woods grown in the United States. U.S. Dep. Agr. Bull. 556, 28 pp., illus.

206. Norin, Torbjorn.
1964. Chanootin, a bicyclic C_{15}-tropolone from the heartwood of *Chamaecyparis nootkatensis* (Lamb.) Spach. Arkiv För. Kem. 22(2): 129-135.

A new C_{15}-tropolone, $C_{15}H_{18}O_3$, has been isolated from the heartwood of *Chamaecyparis nootkatensis*, for which the name chanootin is proposed.

207. _____
1964. The chemistry of the natural order Cupressales. 50. The absolute configurations of chamic, chaminic, and isochamic acids. Arkiv För. Kem. 22(10): 123-128.

Describes the absolute configuration of three chemical substances found in the heartwood of Alaska-cedar.

208. Orloci, Laszlo.
1961. Forest types of the western hemlock zone. M. Sci. thesis, Dep. Biol. & Bot., Univ. Brit. Columbia. 206 pp., illus.

Author presents an ecosystem classification of the forest stands of the coastal western hemlock zone. Alaska-cedar is shown to be an inhabitant of the dry edaphic and mesic zonal forest types of the wet and cool subzone. Alaska-cedar is included in a number of forest types.

209. _____
1963. Indicator plants in the coastal western hemlock zone. *In* 1962 progress report "Ecology of the forests of the Pacific Northwest," V. J. Krajina, ed. pp. 25-34, illus. Univ. Brit. Columbia, Dep. Biol. & Bot.

210. _____
1964. Vegetational and environmental variations in the ecosystems of the coastal western hemlock zone. Ph. D. thesis, Univ. Brit. Columbia, Dep. Biol. & Bot. 204 pp., illus.

211. _____
1965. The coastal western hemlock zone on the southwestern British Columbia mainland: Vegetation-environmental patterns and ecosystem classification. *In* Ecology of western North America, vol. 1. V. J. Krajina, ed. pp. 18-34. Univ. Brit. Columbia, Dep. Bot.

Alaska-cedar is tabulated with its plant associates in the Gaultherieto-Tsugetum heterophyllae association under two ecosystem types; Orthic Vaccinium-Gaultheria type, and Lithosolic Vaccinium-Gaultheria type. Characteristic landform, slope, altitude, and soil characteristics of the habitats are tabulated. Associated tree species on both types are: *Tsuga heterophylla, Thuja plicata, Pseudotsuga menziesii,* and *Pinus monticola.*

212. Osborn, A.
1941. An interesting hybrid conifer: *Cupressocyparis leylandii.* J. Roy. Hort. Soc. 66: 54-55.

Describes natural hybrid between *Cupressus macrocarpa* and *Chamaecyparis nootkatensis.* In the great frost of January 1940 it proved much hardier than *C. macrocarpa.* It is easy to propagate from cuttings, and has been raised from seed.

213. Osgood, Wilfred H.
1901. Natural history of the Queen Charlotte Islands, British Columbia. Natural history of the Cook Inlet Region, Alaska. U.S. Dep. Agr. N. Amer. Fauna 21: 87 pp., illus.

214. Palmer, L. J.
1942. Major vegetative types of southeastern Alaska. U.S. Fish & Wildlife Serv., 16 pp. (Mimeogr.)

215. Paul, B. H.
1961. Choose the right wood. Properties and uses of some minor western softwoods. Hitchcock's Woodworking Dig. 63(10): 26-27.

Tabulates and briefly discusses the sources, supply, physical and mechanical properties, and uses, of Alaska-cedar and several other western conifers.

216. Paul, Benson H.
1959. The effect of environmental factors on wood quality. U.S.D.A. Forest Serv., Forest Prod. Lab. Rep. 2170, 48 pp.

The western cedars, including Alaska-cedar, commonly have highly durable heartwood. Alaska-cedar has a specific gravity of 0.42, higher than other cedars, with growth rates generally 10 and mostly around 20 rings per inch. This slow growth is desirable for certain specialty uses which require uniform structure.

217. Peakes, L. V., Jr., Lloyd, R. A., Barnes, V. S., Berry, J. H., and Ritter, G. J.
1945. Substitute woods for Port-Orford white-cedar for storage battery separators. U.S.D.A. Forest Serv., Forest Prod. Lab. Rep. R1476, 16 pp., illus.

After treatment, Alaska-cedar wood was found to be suitable for use as battery separators. Tests and treatments are described.

218. Peattie, Donald Culross.
1953. A natural history of western trees. 751 pp., illus. Boston: Houghton Mifflin Co.

219. Peavey, George W.
1922. Oregon's commercial forests. Oreg. State Board Forest. Bull. 2 (rev. 1929), 94 pp., illus.

Alaska-cedar is described and mentioned briefly under minor species. The tree occurs between 2,500- and 7,000-foot elevation in Oregon.

220. Peck, Morton Eaton.
1961. A manual of the higher plants of Oregon. Ed. 2, 936 pp., illus. Corvallis: Oreg. State Univ. Press.

221. Penhallow, D. P.
1896. The generaic characters of the North American Taxaceae and Coniferae. Proc & Trans. Roy. Soc. Can., ser. 2, vol. 2, sect. 4, pp. 33-57 plus 6 plates.

222. Penhallow, David Pearce.
1907. A manual of the North American gymnosperms, exclusive of the cycadales but together with certain exotic species. 374 pp. plus 55 plates. Boston: Ginn & Co., Athenaeum Press.

223. Perry, R. S.
1939. Yellow cedar (*Chamaecyparis nootkatensis*) [Lamb.] Spach: its characteristics, properties and uses. British Columbia Lumberman 23: 30-31.

The natural range of the species is the Pacific coast of North America from southern Alaska to northern Oregon. The total estimated stand is about 6 billion board feet, half of which is found on the western side of the coast mountains in British Columbia. It usually grows in mixtures with Sitka spruce, western hemlock, fir, or western redcedar. It averages 85 feet in height and 3 feet in diameter. It is a slow-growing species and is susceptible to heart rot, which makes it difficult to obtain large amounts of high-grade lumber. The wood is clear, yellow in color, straight grained, light in weight, of average strength and toughness, has a low shrinkage factor, and is of high durability. Many of its uses are listed. The strength properties of this and other western commercial species are tabulated.

224. _____
1954. Yellow cedar: its characteristics, properties, and uses. Can. Dep. North. Aff. & Nat. Resources Forest. Br. Bull. 114, 19 pp., illus.

A comprehensive discussion of Alaska-cedar, with emphasis on the tree in British Columbia. Nomenclature, locality, supply, silvical characteristics, wood characteristics, seasoning, workability, finishing, durability, marketing, and uses are discussed, and strength properties tabulated.

225. Phillips, E. W. J.
1948. Identification of softwoods by their microscopic structure. Forest Prod. Res. Bull. 22, London, 56 pp., illus. (Reprinted 1963.)

226. Piper, Charles V.
1906. Flora of the State of Washington. Contrib. U.S. Nat. Herb., Vol. 11, 637 pp., illus.

227. _____ and Beattie, R. Kent.
1915. Flora of the northwest coast, including the area west of the summit of the Cascade Mountains from the 49th parallel south to the Calapooya Mountains on the south border of Lane County, Oregon. 418 pp. Lancaster, Pa.: New Era Printing Co.

228. Platt, Rutherford.
1952. American trees; a book of discovery. 256 pp., illus. New York: Dodd, Mead & Co. (Reprinted 1953 as "A Pocket Guide to the Trees." Cardinal ed. New York: Pocket Books, Inc.)

229. Plummer, Fred G.
1900. Mount Rainier Forest Reserve, Washington. U.S. Geol. Surv. 21st Annu. Rep. 1899-1900, Part 5, Forest Reserves: 81-143, illus.

230. Pomeroy, Kenneth B., and Dixon, Dorothy.
1966. These are the champs. Amer. Forests 72(5): 14-35.

The largest reported Alaska-cedar tree in the United States is located in Mount Rainier National Park, Washington. It is 25 feet 6 inches in circumference, 134 feet high, and has a 25-foot spread.

231. Prentice, R. M.
1963. Forest lepidoptera of Canada, recorded by the forest insect survey. Vol. 1. Lasiocampidae, Thyatiridae, Drepanidae, Geometridae. Can. Dep. Forest., Forest Entomol. Br. Pub. 3 (1013): 283-543, illus.

232. Preston, Richard J., Jr.
1961. North American trees (exclusive of Mexico and tropical United States). Ed. 2, 395 pp., illus. Ames: Iowa State Coll. Press.

Gives the general description, range, and silvical characteristics, of Alaska-cedar.

233. Querengasser, F.
1953-54. Die grune Douglasie (*Pseudotsuga taxifolia*, Douglas fir, red fir) und ihre begleitholzarten. (The green Douglas fir and its associated trees.) Deutsch. Dendrol. Ges. Mitt. 58: 127-141. (In German.)

234. Randall, Warren R.
1965. Manual of Oregon trees and shrubs. 234 pp., illus. Corvallis: Oregon State Univ. Book Stores, Inc.

235. Rayner, R. W.
1963. The diseases of Cupressus and Chamaecyparis. Inter-African Phytosanitary Comm., London. 1-6 pp.

Lists the following disease of Alaska-cedar in the U.S.A.: *Gymnosporangium nootkatense* Trul. Hosts--telial: *Chamaecyparis nootkatensis*, aecial: *Sorbus* spp., *Malus rivularis*. Causes galls of leaves and tender shoots. Listed as a disease of little or no economic importance.

236. Record, Samuel J.
1919. Identification of the economic woods of the United States; including a discussion of the structural and physical properties of wood. Ed. 2 (rev. and enl.), 157 pp. plus 6 plates. New York: John Wiley & Sons, Inc.; London: Chapman & Hall, Ltd.

Wood identification with key.

237. _____
1934. Identification of the timbers of temperate North America, including anatomy and certain physical properties of wood. 196 pp. plus 6 plates. New York: John Wiley & Sons, Inc.

238. _____ and Hess, Robert W.
1943. Timbers of the new world. 640 pp., illus. New Haven: Yale Univ. Press.

239. Rehder, A.
1940. Manual of cultivated trees and shrubs hardy in North America. Ed. 2 (rev. and enl.), 996 pp., illus. New York: Macmillan Co. (Reprinted 1947, 1949.)

240. Rehder, Alfred.
1949. Bibliography of cultivated trees and shrubs hardy in the cooler temperate regions of the northern hemisphere. Arnold Arboretum, Harvard Univ., 825 pp.

Gives 31 references to the sources of botanical names, valid names, and synonyms.

241. Rennerfelt, Erik, and Nacht, Gertrud.
1955. The fungicidal activity of some constituents from heartwood of conifers. Svensk Bot. Tidskr. 49(3): 419-432.

Nootkatin, a heartwood substance from Alaska-cedar, was found to inhibit fungus growth at 0.001- to 0.002-percent concentrations. Chamic acid from Alaska-cedar heartwood inhibited fungi at 0.01-0.02 percent.

242. Resch, Helmuth, and Ecklund, Barton A.
1963. Moisture content determination for wood with highly volatile constituents. Forest. Prod. J. 13(11): 481-482.

The high volatile-oil content of Port-Orford-cedar and Alaska-cedar affected moisture determination by the oven method. Correction factors for electrical resistance meters were based on moisture determinations by the Karl Fischer method, which were consistently lower.

243. _____ and Ecklund, Barton A.
1963. Electrical moisture meter calibration for woods containing highly volatile constituents. Calif. Forest., Forest Prod. 34: 1-4.

244. Robinson, Robena Claire.
1960. Black stain in yellow cedar *Chamaecyparis nootkatensis* (D. Don) Spach. M.A. thesis, Univ. Brit. Columbia, Dep. Biol. & Bot. 54 pp. illus.

245. Rowe, J. S.
1959. Forest regions of Canada. Can. Dep. North. Aff. & Nat. Resources Forest. Br. Bull. 123, 71 pp., illus. (Revision of "A forest classification for Canada," by W. E. D. Halliday, Can. Dep. North. Aff. & Natur. Resources Bull. 89. 1937.)

246. Rudnicki, J. M.
1951. Timber fasteners. *In* Canadian woods; their properties and uses. Ed. 2, pp. 305-320, illus. Ottawa: King's Printer.

247. St. John, Harold, and Hardin, Edith.
1929. Flora of Mt. Baker. Mazama 11(12): 52-102, illus.

248. _____ and Warren, Fred A.
1937. The plants of Mount Rainier National Park, Washington. Amer. Midland Natur. 18(6): 952-957.

249. Sargent, C. S.
1885. The woods of the United States. With an account of their structure, qualities, and uses. With geographical and other notes upon the trees which produce them. 203 pp., illus. New York: D. Appleton & Co.

250. Sargent Charles S.
1884. Report on the forests of North America (exclusive of Mexico). 612 pp., illus. U.S. Dep. Int., Census Off.

Gives a brief description of the tree and its occurrence in the United States, with information on wood properties.

251. Sargent, Charles Sprague.
1933. Manual of the trees of North America (exclusive of Mexico). Ed. 2, 910 pp., illus. Boston, New York: Houghton Mifflin Co. (Reprinted 1961. 2 vol. New York: Dover Publ., Inc.)

252. Scheffer, T. C., and Eslyn, W. E.
1961. Effect of heat on the decay resistance of wood. Forest Prod. J. 11(10): 485-490.

Wet-heating schedules lowered decay resistance of some species tested, including Alaska-cedar. No decrease in resistance occurred at 180° F. for 48 hours, but decay resistance was lowered after heating for 1 hour at 300° F.

253. Schmidt, R. L.
1955. Some aspects of western redcedar regeneration in the coastal forests of British Columbia. Brit. Columbia Forest Serv. Res. Note 29, 10 pp., illus.

Adventitious rooting of yellow cedar was noted on Vancouver Island.

254. _____
1958. Climate and the altitudinal distribution of conifers. Brit. Columbia Forest Serv., Forest Res. Rev. 1957: p. 14.

Describes a study in Elk Valley, Vancouver Island, on two aspects between 1,000 and 4,600 feet. Length of the frost-free season decreased at the rate of 2.8 days per 500 feet of elevation within the altitudinal range of Douglas-fir, western hemlock, and western redcedar, but above this level the frost-free season decreased 36 days in 500 feet. Alaska-cedar, subalpine fir, Pacific silver fir, and mountain hemlock were not affected by the temperature boundary. Alaska-cedar occurs from 1,000- to 5,000-foot elevation at the study site.

255. Scott, David R. M.
1962. Plant associations of western Washington. Univ. Wash. Arboretum Bull. 25: 11-14, 26.

256. Shaw, C. G., and Harris, M. R.
1960. Important diseases and decays of trees native to Washington. Wash. State Univ. Agr. Ext. Serv. Bull. 540, 35 pp.

257. Shaw, Charles Gardner.
1958. Host fungus index for the Pacific Northwest. I. Hosts. Wash. Agr. Exp. Sta. Circ. 335, 127 pp.

258. Sheldon, E. P.
1904. The forest wealth of Oregon. 32 pp., illus. Lewis & Clark Exposition Comm., Portland.

259. Sigafoos, Robert S.
1958. Vegetation of northwestern North America, as an aid in interpretation of geologic data. U.S. Geol. Surv. Bull. 1061-E: 165-185, illus.

260. Slavin, Arthur D.
1931. Some conifers cultivated in the United States. *In* Conifers in cultivation: the report of the conifer conference held by the Royal Horticultural Society. pp. 86-150, illus. London: Roy. Hort. Soc.

Describes many species, including Alaska-cedar, grown in several aboreta in the U.S.

261. Smith, J. H. G., and Ker, J. W.
1957. Timber volume depends on D^2H. British Columbia Lumberman 41(9): 28, 30.

Constants a and b for 24 tree species are given for the combined variable formula in which tree volume (V) is estimated in terms of d.b.h. squared (D^2) and total height (H).

$$V = a + b \frac{D^2H}{100}$$

The same constants are used for Alaska-cedar and western redcedar, a set being tabulated separately for coast immature, coast mature, and interior trees, by diameter classes of 0 to 26 inches and 27 inches and above. Standard errors for very tall and very short trees are also tabulated.

262. Smith, J. Harry G., and Breadon, Robert E.
1964. Combined variable equations and volume-basal area ratios for total cubic-foot volumes of the commercial trees of B.C. Forest. Chron. 40: 258-261.

263. Society of American Foresters.
1954. Forest cover types of North America (exclusive of Mexico). Report of the committee on forest types. 67 pp.

The timber types containing Alaska-cedar have been slightly modified in the 1964 edition.

264. _____
1964. Forest cover types of North America (exclusive of Mexico). 67 pp.

A description of the composition, nature, and occurrence of the following numbered timber types in which Alaska-cedar occurs in mixture with other tree species: high elevations (in the mountains), mountain hemlock-subalpine fir (205); middle elevations (interior), western hemlock (224), Pacific silver fir-hemlock (226), western redcedar-western hemlock (227), western redcedar (228).

265. Sødergaard, Poul.
1965. Kimplanternes morfologi og udvikling hos de I skovbruget almindeligt anvendte naletraeer. (Identification of 1 and 2 year seedlings of 25 conifers.) Dansk Dendrol. Arsskr. 2(11): 185-247, illus. (In Danish.)

266. Southwood, T. R. E.
1962. *Chamaecyparis nootkatensis* (D. Don) Spach a new host plant for *Cyphostethus tristriatus* (F.) (Hem., Acanthosomatidae). Entomol. Monogr. 98(1180/1183): 250.

Cyphostethus tristriatus (F.), a green and brown bug, formerly thought to be virtually monophagous on *Juniperus communis* L., was found to feed and breed on *Chamaecyparis nootkatensis* planted in Ascot, Berkshire.

267. Spada, Benjamin.
1962. Forest statistics for Pierce County, Washington. U.S.D.A. Forest Serv., Pacific Northwest Forest & Range Exp. Sta. Forest Surv. Rep. 141, 26 pp., illus.

Volume of Alaska-cedar growing stock in Pierce County, Washington, in 1959 was reported to be 16 million board feet (International 1/4-inch rule). Volume of sawtimber on commercial forest land was 15 million board feet (Scribner). Area of commercial forest land occupied by Alaska-cedar type was 1,000 acres, all of which was in public ownership.

268. _____ and Usher, Jack H.
1955. Forest statistics for Yakima County, Washington. U.S.D.A. Forest Serv., Pacific Northwest Forest & Range Exp. Sta., Forest Surv. Rep. 121, 29 pp.

269. Spaulding, Perley.
1956. Diseases of North American forest trees planted abroad. An annotated list. U.S. Dep. Agr. Handb. 100, 144 pp.

270. Stamm, Alfred J.
1929. The capillary structure of softwoods. J. Agr. Res. 38: 23-67.

Examines in detail, by dynamic physical methods, the capillary structure of six western conifers, including Alaska-cedar.

271. Stone, Herbert.
1904. The timbers of commerce and their identification. 311 pp., illus. London: William Rider & Son, Ltd.

272. Streets, R. J.
1962. Exotic forest trees in the British Commonwealth. 765 pp., illus. Oxford: Clarendon Press.

273. Sudworth, George B.
1897. Nomenclature of the arborescent flora of the United States. U.S. Dep. Agr. Div. Forest. Bull. 14, 417 pp.

274. _____
1898. Check list of the forest trees of the United States, their names and ranges. U.S. Dep. Agr. Bull. 17, 144 pp.

Lists the following common names in use: yellow cedar, Sitka cypress, yellow cypress, Nootka cypress, Nootka Sound cypress, Alaska ground cypress, Alaska cypress. Fourteen varieties are distinguished in cultivation: *viridifolia* Sudw., *cinerascens* Sudw., *cinerascens genuina* Sudw.,

cinerascens aureo-discolor Sudw., *argenteo-varians* Sudw., *aureo-versicolor* Sudw., *zanthophylla* Sudw., *pendens* Sudw., *compacta* (Veitch) Beissn., *compressa* Beissn., *nidiformis* Beissn., *albo-picta* Sudw., *aureo-viridis* (Hort. Kew.) Sudw., *picta* Sudw. Accepted scientific and common names are, *Chamaecyparis nootkatensis* (Lamb.) Spach, yellow cedar.

275. _____
1908. Forest trees of the Pacific slope. U.S. Dep. Agr., 441 pp.

276. _____
1927. Check list of the forest trees of the United States, their names and ranges. U.S. Dep. Agr. Misc. Circ. 92, 295 pp.

277. Taylor, R. F., and Little, E. L., Jr.
1950. Pocket guide to Alaska trees. U.S. Dep. Agr. Handb. 5, 63 pp., illus. (Revision of Misc. Pub. 55.)

278. Taylor, Walter P.
1922. A distributional and ecological study of Mount Rainier, Washington. Ecology 3: 214-236.

279. Tessier, J. P., and Knapp, F. M.
1961. Cost analysis of a mobile logging operation on the U. B. C. research forest. Univ. Brit. Columbia Fac. Forest. Res. Pap. 41, 16 pp., illus.

Gives log specifications used in bucking.

280. Titmuss, F. H.
1965. Commercial timbers of the world. Ed. 3, enl., 277 pp. London: Technical Press, Ltd.

Briefly describes Alaska-cedar wood.

281. Troll, C.
1955. Der Mount Rainier und das mittlere Cascaden-Gebirge. (Mount Rainier and the middle Cascade mountains.) Erkunde 9: 264-274, illus. (In German.)

282. Troup, R. S.
1932. Exotic forest trees in the British Empire. 259 pp. Oxford: Clarendon Press.

283. U.S.D.A. Forest Service.
1948. Woody-plant seed manual. U.S. Dep. Agr. Misc. Pub. 654, 416 pp., illus.

One pound of cleaned seed contains from 66,000 to 180,000 seeds, with an average of 108,000. Germination is characteristically low with germinative capacity ranging from 0 to 2 percent and potential germination from 22 to 57 percent. Stratification for 60-90 days at 41° F. is recommended to break embryo dormancy. The seed is fragile.

284. _____
1955. Wood handbook. U.S. Dep. Agr. Handb. 72, 528 pp., illus.

Contains basic information on wood as a material of construction with data for its use in design and specification.

285. _____
1961. Standard terms for describing wood. Ed. 3 (rev.), 12 pp. Forest Prod. Lab.

Presents a series of standard terms for describing properties of various species of wood, including Alaska-cedar, as developed by the Forest Products Laboratory.

286. _____
1963. Characteristics of Alaska woods. Forest Prod. Lab. U.S.D.A. Forest Serv. Res. Pap. FPL-1, 64 pp., illus., tables.

A general discussion of mechanical properties, pulp and papermaking characteristics, seasoning data, and preservative treatment of various Alaska woods, including Alaska-cedar. Includes summary tables on strength properties, pulp processes and yields, and drying schedules.

287. _____
1966. 1966 seed and planting stock dealers. Tree Planters' Note 78, 29 pp.

The directory lists four sources of Alaska-cedar seed and one source of planting stock.

288. Van Dersal, William R.
1938. Native woody plants of the United States, their erosion control and wildlife values. U.S. Dep. Agr. Misc. Pub. 303, 362 pp., illus.

289. Veer, J. J. G., and King, F. W.
1963. Moisture blistering of paints on house siding. Can. Dep. Forest. Pub. 1024, 25 pp., illus.

Free water is necessary for paint blistering and water vapor alone does not cause it. Susceptiblity to paint blistering decreased by species in this order: *Thuja plicata, Pseudotsuga taxifolia, Chamaecyparis nootkatensis, Pinus strobus, Juniperus virginiana, Pinus resinosa,* and *Picea* spp.

290. Verrall, Arthur F.
1968. Poria incrassata rot: Prevention and control in buildings. U.S. Dep. Agr. Tech. Bull. 1385, 27 pp., illus.

291. Wade, Leslie Keith.
1965. Plant associations of the sphagnum bog ecosystem at Tofino, Vancouver Island. *In* 1964 progress report "Ecology of the forests of the Pacific Northwest," V. J. Krajina, ed. pp. 15-16. Univ. Brit. Columbia, Dep. Biol. & Bot.

A report on the vegetation of a marine terrace adjacent to the coastal beaches of Wickannish Bay, near Tofino, Vancouver Island. Ten tentative plant community types are described, two of which contain Alaska-cedar: *Pinus contorta-Chamaecyparis nootkatensis*--a community restricted to bog periphery and incorporating both bog and forest elements in its composition--and Bog Forest--a forest of characteristically dwarfed conifers surrounding the bog area. The latter is extensive and probably represents the final stage in succession from the bog. The dwarfed and peculiarly shaped condition of the trees is due to poor drainage and scarcity of nutrients. Principal trees are *Pinus contorta*, *Thuja plicata*, *C. nootkatensis*, *Tsuga heterophylla*, and *Taxus brevifolia*.

292. West, W. I.
1949. A collection of Oregon woods: Prog. Rep. 1., Circ. 1, 31 pp., illus. Corvallis: Oreg. State Coll.

Purpose of the report was to make the collection's existence known. Lists seven specimens of Alaska-cedar.

293. Whitford, H. N., and Craig, Ronald D.
1918. Forests of British Columbia. 409 pp., illus. Can. Comm. Conserv., Ottawa.

In the vicinity of the Strait of Georgia, Alaska-cedar is seldom found below 2,000 feet and extends up to 5,000 feet. Northward, it gradually descends to tidewater at Knight Inlet. Clear yellow cypress is perhaps the highest priced lumber produced in the province, as high as $100 per thousand board feet having been paid for it by local boatbuilders. There is an estimated 4,056,000,000 board feet of standing timber in the province.

294. Whittaker, R. H.
1961. Vegetation history of the Pacific Coast States and the central significance of the Klamath region. Madrono 16: 5-23.

The range of Alaska-cedar in the Klamath region suggests that it is a relict from glacial time. It is confined to three isolated patches in the extreme southern end of its range, two of these reported by Mason (1941) and one found by the author on Preston Peak.

295. Winkenwerder, Hugo.
1920. Short keys to the trees of Oregon and Washington. 16 pp. Seattle: Univ. Wash. Press.

296. Witt, J. A.
1959. A cross section of arboretum plant introductions. Univ. Wash. Arboretum Bull. 22(4): 121-123, 138.

Cupressocyparis leylandii has been planted in the University of Washington arboretum and has made good growth. It promises to be one of the best evergreen screening and hedge plants for the area.

297. Wolf, Carl B.
1948. The new world cypresses. Part I, Taxonomic and distributional studies of the new world cypresses. El Aliso 1: 1-250.

The author quotes in its entirety an article describing hybridization between *Cupressus macrocarpa* and *Chamaecyparis nootkatensis* (Jackson, A. B., and Dallimore, W., 1926. A new hybrid conifer. Bull. Misc. Inf. Kew. 3, 113-114). The author states that he had not seen either living or pressed specimens of the resulting hybrid (*Cupressocyparis leylandii*), but that the evidence presented by Jackson and Dallimore for its origin is convincing, and he concedes that they are probably correct in their conclusion.

298. Wood, R. F.
1955. Studies of north-west American forests in relation to silviculture in Great Britain. Brit. Forest. Comm. Bull. 25, 42 pp., illus.

There appears to be no generalized climatic limit in Great Britain for *Chamaecyparis nootkatensis*. The species has low requirements and is worthy of trial at high elevations.

299. Wyman, Donald.
1951. Trees for American gardens. 376 pp., illus. New York: Macmillan Co.

The species does not have a wide distribution in the United States because it requires a moist climate. It is not used much on the Pacific coast, but is considered one of the finest trees where it can be grown.

300. Zavarin, Eugene, Smith, Rosalin M., and Anderson, Arthur B.
1959. Paper chromatography of the tropolones of Cuppressaceae. II. J. Org. Chem. 24(9): 1318-1321.

Heartwood of 14 species of Cupressaceae were examined by paper partition chromatography for the tropolones present, and the results are discussed.

301. Zehetmayr, J. W. L.
1954. Experiments in tree planting on peat. Brit. Forest. Comm. Bull. 22, 110 pp., illus.

In tests on *Scirpus-Calluna-Molina*, Alaska-cedar has grown slowly, even when fertilized with phosphate, with heights of 3 feet at 12 years after planting. Unfertilized controls reached 2 feet in height. On poorer soil, Alaska-cedar reached 3 to 4 feet 16 years after planting. Smaller plants were damaged by frost in the spring of 1947.

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COMMON AND SCIENTIFIC NAMES OF TREE SPECIES MENTIONED IN LITERATURE REFERENCES

Alaska-cedar	*Chamaecyparis nootkatensis* (D. Don) Spach
Atlantic white-cedar	*Chamaecyparis thyoides* (L.) B. S. P.
Baldcypress	*Taxodium distichum* (L.) Rich.
Brewer's spruce	*Picea breweriana* S. Wats.
California red fir	*Abies magnifica* A. Murr.
Common juniper	*Juniperus communis* L.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Eastern redcedar	*Juniperus virginiana* L.
Eastern white pine	*Pinus strobus* L.
Englemann spruce	*Picea engelmannii* Parry
Grand fir	*Abies grandis* (Dougl.) Lindl.
Hiba Arbor-vitae	*Thujopsis dolabrata* (Lif.) Sieb. & Zucc.
Hinoki cypress	*Chamaecyparis obtusa* (Sieb. & Zucc.)
Incense-cedar	*Libocedrus decurrens* Torr.
Leyland cypress	*Cupressocyparis leylandii*
Lodgepole pine	*Pinus contorta* Dougl.
Monterey cypress	*Cupressus macrocarpa* Hartw.
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carr.
Noble fir	*Abies procera* Rehd.
Northern white-cedar	*Thuja occidentalis* L.
Pacific silver fir	*Abies amabilis* (Dougl.) Forbes
Pacific yew	*Taxus brevifolia* Nutt.
Para angelwood	*Dicorynic paraensis*
Port-Orford-cedar	*Chamaecyparis lawsoniana* (A. Murr.) Parl.
Red pine	*Pinus resinosa* Ait.
Redwood	*Sequoia sempervirens* (D. Don) Endl.

Shasta red fir	*Abies magnifica* var. *shastensis* Lemm.
Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.
Western larch	*Larix occidentalis* Nutt.
Western redcedar	*Thuja plicata* Donn
Western white pine	*Pinus monticola* Dougl.
Whitebark pine	*Pinus albicaulis* Engelm.
White oak	*Quercus alba* L.

Harris, A. S.
1969. Alaska-cedar. A bibliography with abstracts. U.S.D.A. Forest Serv. Res. Pap. PNW-73, 47 pp. Pacific Northwest Forest & Range Exp. Sta., Portland, Oregon.

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ebb-Pomerene Export Trade Associations and the Wood Products Industries

or

Can the Webb-Pomerene Act Help the S. Sell More Processed Wood to Japan?

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Portland, Oregon 1969

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The author conducted this study while employed by the Pacific Northwest Forest and Range Experiment Station. He is currently employed by the forestry consulting firm of Mason, Bruce, and Girard in Portland, Oregon.

U.S.D.A. Forest Service Research Paper PNW-74

WEBB-POMERENE EXPORT TRADE ASSOCIATIONS AND THE WOOD PRODUCTS INDUSTRIES

or

CAN THE WEBB-POMERENE ACT HELP THE U.S. SELL MORE PROCESSED WOOD TO JAPAN?

by

John H. Beuter

1969

PACIFIC NORTHWEST
FOREST AND RANGE EXPERIMENT STATION

Philip A. Briegleb, Director
FOREST SERVICE

Portland, Oregon
U.S. Department of Agriculture

INTRODUCTION

West coast wood processors are striving to find effective ways to increase the sale of processed wood products in Japan. It is generally agreed that wood products trade with Japan is desirable. However, the mix of wood products exported in the past few years, consisting of large volumes of logs and relatively little lumber and plywood, is unsatisfactory to a large segment of the wood products industries (table 1). In particular, the lumber industry is seeking to increase the opportunity to process some of the logs now being exported and assist in meeting the Japanese demand for wood by shipping more processed wood and fewer logs to Japan.

Not the least among the barriers to effectively marketing processed wood products in Japan is the competitive nature of the wood products industries. Mead (1964)[1/] ranks the lumber industry among the most competitive in the U.S. economy in terms of a large number of firms and a product that cannot generally be differentiated as to the firm which produced it. This competitiveness exists primarily in the domestic markets for wood products. To most mills, nondomestic markets, if they are even recognized, are a sideline to be turned on and off as conditions in the domestic markets change. These mills feel they have a niche in the highly competitive domestic market and that to turn to nondomestic markets is to risk the loss of that niche which they might never regain. Thus, it is understandable that few mills, acting as individual producers, are willing to actively seek new markets overseas.

1/ Names and dates in porentheses refer to literature cited in "Bibliography," p. 14.

Table 1. — **Exports of logs, lumber, and plywood to Japan from Oregon and Washington ports, 1961-67**

Year	Logs[1/]	Lumber[1/]	Softwood plywood[2/]
	M bd. ft., Scribner log scale	M bd. ft., lumber tally	M sq. ft., 3/8-inch basis
1961	328,116	108,791	([3/])
1962	286,655	37,975	([3/])
1963	638,722	49,705	([3/])
1964	739,692	33,393	240
1965	774,908	21,035	539
1966	1,023,242	26,169	2,833
1967	1,494,233	48,057	6,351

1/ Austin ond Hamiltan (1968).
2/ Source: U.S. Department of Commerce.
3/ Not ovoilable.

Also a problem is the lack of exporting information and experience among the personnel of small firms. In a study of why small firms don't export, Grokë and Kreidle (1968) found that the major reasons were:

1. Lack of foreign market information.
2. Fear of foreign competition.
3. Export selling difficulties.

The major export selling difficulties cited were:

1. Government restrictions.
2. Cargo documentation.
3. Segmented markets.
4. Cost and nonavailability of shipping.
5. Foreign administrative problems.

Again, it is understandable why a small firm, wishing to preserve its domestic market position, would be reluctant to get involved with foreign markets. To overcome difficulties such as those cited above would require an all-out effort — not just occasional interest.

The Federal Trade Commission (FTC) recognized some of these problems as early as 1916 in a report which indicated that small businessmen were disadvantaged in attempting to enter foreign markets individually (Federal Trade Commission 1916). The major reasons cited at that time were combinations of foreign competitors (sellers) and organized buyers—particularly the buying cartels which existed in Germany. This report sparked the introduction of a bill in the U.S. Congress which would allow American firms to cooperate in export trade. This bill eventually emerged as the Webb-Pomerene Export Trade Act of 1918 (Public—No. 126—65th Congress) (H.R. 2316).

The purpose of this report is to bring the Webb-Pomerene Act to the attention of those associated with the wood products industries who are seeking information about export marketing. The general provisions, intent, and performance of the Act will be discussed first to acquaint the reader with the Act. The remainder of the report will discuss the past and potential use of the Act by the wood products industries with a particular focus on the west coast.

THE WEBB-POMERENE ACT

Provisions and Intent of the Act

The Webb-Pomerene Act, or the Webb Act as it is commonly referred to, has two provisions which, in effect, allow firms to cooperate for the purposes of export trade in a way that is illegal for purposes of domestic trade:

1. **Section 2 provides that any association established for the sole purpose of engaging in export trade[2/] is exempt from the Sherman Antitrust Act, including any actions it undertakes and agreements it makes in the course of export trade. This exemption is qualified in that the association through its acts or agreements cannot:**
   a. **Restrain trade within the United States.**
   b. **Restrain the export trade of any domestic competitor of the association.**
   c. **Artificially or intentionally influence prices within the United States of commodities of the class exported by such association.**
2. **Section 3 provides an exemption from the merger provisions of section 7 of the Clayton Act and allows competing sellers to join together in an export association.**

The intent of Congress was to assist small firms that were financially unable to conduct individual export programs and to assist firms which faced cartels abroad. Specifically, Congress believed that firms could benefit in the following ways under the Webb Act (Federal Trade Commission 1967, pp. 4-8):

1. The costs of exporting would be reduced either by spreading overhead and eliminat-

2/ Export trade is defined in section 1 of the Webb Act as "solely trade or commerce in goods, wares or merchandise exported or in course of being exported from the United States or any Territory thereof to any foreign nation."

ing duplicate sales organizations, or by obtaining lower rates on export services such as insurance and freight, or by increasing the line of merchandise offered for export.

2. Groups of relatively smaller scale American producers would more readily be able to enter into and survive in foreign markets in the face of powerful combinations, because of their reduced export costs and increased financial resources supporting export programs.
3. Higher prices and improved sales terms generally would be obtained from foreign buyers, especially those organized into buying cartels, due to the elimination of competition among American firms.
4. Lower shipping rates and other export service charges would be obtained due to organized and concerted effort of the associations.

Administration of the Act

Sections 4 and 5 of the Webb Act provide broad administrative guidelines. In essence, the Federal Trade Commission is the administrator with its jurisdiction expanded by the provisions of section 4 to include acts committed outside the United States. Associations are required to register with the FTC within 30 days of formation and are required to furnish the Commission, upon request, information about the association's organization, business, conduct, practices, and management relation with other associations, corporations, partnerships, and individuals. The Commission has the authority to investigate alleged violations of the Webb Act by associations and to make recommendations to associations for adjustments in their activities. If an association chooses to ignore the Commission's recommendations, the Commission may refer its findings to the U.S. Attorney General for appropriate action.

General Performance Under the Act

From 1918 through 1965, 258 associations registered under the Webb Act. Eighty-two of these registrations did not conform to the provisions of the Act and thus were not valid. Of the remaining 176 registrations, only 130 were active during any time of their existence. There were 29 active associations in 1965.

Since 1920, exports under the Webb Act have averaged 4.8 percent of total United States exports, according to annual data provided to the FTC. This figure is considered an overstatement because many associations reported all exports by member firms whether Webb assisted or not. A survey by the FTC showed that actual Webb-assisted exports averaged only 2.4 percent of total U.S. exports from 1958 to 1962, compared with around 5 percent as calculated from FTC reports (Federal Trade Commission 1967, pp. 23-60).

A Federal Trade Commission staff report contains a detailed history and analysis of Webb associations from 1918 to the present (Federal Trade Commission 1967). For the purposes of this paper, it will suffice to sum up the performance under the Webb Act by quoting Dr. Willard F. Mueller, Director of the Bureau of Economics, Federal Trade Commission:[3/]

> The most striking impression to be goined from o review of [Webb] ossociotion activities is how insignificant such associotions ore in overall U.S. export trade. They are few in number, representing only o hondful of products, ond their octivities (with o few exceptions) are narrow, embrocing little more than those engaged in by domestic trode ossociations. Nor are the associations used to counteract foreign cartels. Cleorly, the Webb-Pomerene Act, extending limited onti-trust exemption for cooperotive business groups engoged in export trade, hos not opened o significont channel for the exponsion of export trode. Although, **a priori**, export cooperotion can be expected to play o significant role in reducing trode barriers by reducing export costs, improving morket knowledge, and strengthening borgaining advantages, o half century of experience indicotes thot the odvantages conferred ore limited. The right to form Webb Associotions has been exercised by few firms and proportionotely even fewer smoll firms. More often than not those exercising the right were least in need of it, being capable of supporting export programs on their own occounts ond, in fact, typicolly doing so. The most thot con be soid for the Webb-Pomerene Act is thot its implementation opened up o new option for developing trode. However, it hos proven to be an option rarely exercised by members of the business community.

3/ Given in testimony before the Subcommittee on Antitrust and Monopoly of the Committee on the Judiciory, United States Senate, June 26, 1967 (see olso Federol Trode Commission 1967, p. 59).

Despite the rather dismal overall history of performance under the Webb Act, there have been some specific instances of successful associations. Successful associations usually have one major factor in common: The member firms produce a homogeneous product. That is, the product generally has the same characteristics and quality regardless of which member firm produced it. Three product categories accounting for a majority of the active Webb associations have been: food products, chemicals (mostly fertilizer raw materials), and wood and paper products. It is the latter product category that will now be examined in some detail with regard to Webb-assisted activity.

THE WEBB-POMERENE ACT AND THE WOOD PRODUCTS INDUSTRY

General History

From April 1918 to the present, 30 wood products export associations were legitimately registered under the provisions of the Webb Act[4/] (table 2). The length of life of these associations varied, but overall, the wood products associations were among the more durable in comparison with associations from all other commodity groups (table 3).

The use of the Webb Act by the wood products industries has declined steadily since the mid-1930's (table 4). At present, only three wood products export associations are registered: Pulp, Paper, and Paperboard Export Association of the United States (formerly Kraft Products); Plywood International; and Walnut Export Sales Company, Inc. Plywood International is presently inactive.

It is interesting to note that from 1958 to 1968, a period of increasing international demand for wood products, Webb associations in the wood products industries have continued to decline in number and activity. This is particularly notable on the west coast where the 1967 purchases of logs by the Japanese were over 16 times what they were in 1960 — and where not a single wood products Webb association is now active.

4/ Two other associations were registered but were later found not to meet the requirements as defined by the Webb Act.

Table 2 — **Firms registering under the Webb-Pomerene Act for purposes of export trade in wood products, 1918-68**

Name and address	Years reporting to FTC	Years active	Products	Total number of members[1/]
1. Alabama-Florida Pitch Pine Export Association Pensacola, Fla.	1929-33	1929-32	Lumber	6
2. American Box Shook Export Association Washington, D.C.	1935-46	1937-45	Wooden shook	23
3. American Export Door Association Tacoma, Wash.	1927-30	1927-29	Wooden doors	10

Table 2 — **Firms registering under the Webb-Pomerene Act for purposes of export trade in wood products, 1918-68** (continued)

Name and address	Years reporting to FTC	Years active	Products	Total number of members[1/]
4. American Export Lumber Corp. Philadelphia, Pa.	1919-20	([2/])	Lumber	(51)
5. American Hardwood Exporters New Orleans, La.	1930-52	1930-52	Hardwood lumber	9
6. American Paper Exports, Inc. New York, N. Y.	1918-41	1918-41	Paper and paperboard	61
7. American Pitch-Pine Export Co. Wilmington, Del.	1919-35	1919-35	Lumber and timber	15
8. American Pulp Export Corp. of New York New York, N. Y.	1941-42	([2/])	Woodpulp and related products	(6)
9. Atlantic & Gulf Export Co. Jacksonville, Fla.	1921-	([2/])	Naval stores (rosin and turpentine)	(38)
10. Carolina Wood Export Corp. Wilmington, Del.	1919-23	([2/])	Lumber and wood products	(14)
11. Delta Export Lumber Corp. Memphis, Tenn.	1922-26	1922-25	Red gum forest products, lumber and logs	31
12. Door Export Co. Tacoma, Wash.	1944-58	1944-58	Wooden doors	8
13. Douglas Fir Export Co. (formerly Douglas Fir Exploitation & Export Co.) Seattle, Wash.	1918-60	1918-59	Lumber and logs	277
14. Easco Lumber Association San Francisco, Calif.	1941-53	1941-43 1946-49	Lumber	4
15. Florida Pine Export Association Jacksonville, Fla.	1930-31	([2/])	Yellow pine lumber and timber	(6)

Table 2 — **Firms registering under the Webb-Pomerene Act for purposes of export trade in wood products, 1918-68** (continued)

Name and address	Years reporting to FTC	Years active	Products	Total number of members[1/]
16. Gulf Pitch Pine Export Association New Orleans, La.	1920-33	1920-31	Lumber	7
17. International Wood Naval Stores Export Corp. Gulfport, Miss.	1939-41	([2/])	Rosin and turpentine	(8)
18. Naval Stores Corp. New Orleans, La.	1923-30	1923-28	Rosin and turpentine	39
19. Northwest Lumber Exporters Association Seattle, Wash.	1929-31	([2/])	Lumber	(26)
20. Pacific Forest Industries Tacoma, Wash.	1935-64	1935-64	Plywood	36
21. Plywood International Seattle, Wash.	1964-	1964-67	Plywood	26
22. Pulp, Paper, and Paperboard Export Association (formerly Kraft Export Association of U.S.) New York, N. Y.	1952-	1952-	Paper and tall oil	19
23. Redwood Export Co. San Francisco, Calif.	1918-60	1918-56	Lumber	20
24. Rosin and Turpentine Export Co., Inc. New York, N. Y.	1923	([2/])	Rosin and turpentine	Not available
25. United Export Lumber Association Seattle, Wash.	1931-32	([2/])	Lumber	(3)
26. United States Forest Products.Co. Kansas City, Mo.	1919-22	([2/])	Not available	(13)
27. United States Handle Export Co. Piqua, Ohio	1919-39	1919-31	Wooden handles	15

Table 2 — **Firms registering under the Webb-Pomerene Act for purposes of export trade in wood products, 1918-68** (continued)

Name and address	Years reporting to FTC	Years active	Products	Total number of members[1/]
28. Walnut Export Sales Co., Inc. Indianapolis, Ind.	1919-	1919-42 1945-	Walnut lumber	19
29. Wescosa Lumber Association (formerly Wesco) San Francisco, Calif.	1941-61	1941-61	Lumber	4
30. Western Plywood Export Co. Seattle, Wash.	1926-36	1927-35	Plywood	27

Source: Federal Trade Commission (1967, pp. 88-101).
1/ Figures in parentheses indicate membership at time of registration.
2/ Never become fully active.

Table 3 — **Type of product represented in relation to length of life of Webb association**

Commodity group	Length of life of association		
	1-5 years	5-20 years	20+ years
	Percent		
Wood and paper	23	50	27
Chemicals	42	17	42
Food	65	23	13
Nonmetallic minerals	56	22	22
Textiles	25	50	25
Machinery	35	59	6
Miscellaneous	36	55	9
All associations	42	39	19

Source: Federal Trade Commission (1967, p. 32).

Table 4 — **Number of wood products exporting associations registered under the Webb Act, by period, 1918-68**

Period	Number registered	Number active
1918-30	20	13
1931-40	16	12
1941-50	12	10
1951-60	9	8
1961-64	5	5
1965	3	3
1966	3	3
1967	3	3
1968	3	2

Source: Federal Trade Commission (1967, pp. 88-101).

Wood Products Webb Associations in Western United States

Of the 30 wood products Webb associations registered since 1918, 11 had their main offices on the Pacific coast and their activity, if any, was primarily associated with western wood products (table 2).[5/]

Of the 11 Pacific coast Webb associations, only nine ever recorded any activity. The most important of the nine for the purposes of this analysis are: Douglas Fir Export Co., Pacific Forest Industries, and Plywood International. The first two are important because of their length of active operation and apparent success; the latter is important because of its recent (1964) beginning. The functions of these Webb associations are shown in table 5.

Douglas Fir Export Co.—The Douglas Fir Export Co. began as the Douglas Fir Exploitation & Export Co. (Douglas Fir Ex. and Ex.) in 1913. The company was incorporated in Seattle, Wash., and eventually established branch offices in San Francisco and Portland. There were five members at the time of incorporation and about 30 members when the company officially began operation on October 11, 1916.

The purpose of the company is stated in the following excerpt from its bylaws:[6/]

> The carporatian having been farmed far the primary purpase af stimulating and enlarging the use of and market for Pacific Caast farest products in the fareign countries of the warld, by assaciating together of as many af the Pacific Coast lumber manufacturers as will join in the same, with a view af handling the foreign carga shipments of such manufacturers far a brokerage commissian sufficiently large to enable this corporation out af its net earnings to carry an an energetic and comprehensive plan far increasing fareign trade in Pacific Caast lumber products, and with a further view that all the stackhalders af this carparatian, whether large ar small, shall have an equal vaice in its management and cantribute equitably through the payment af such brakerage ta the expenses invalved in such explaitatian. . . .

5/ The presently active Pulp, Poper, ond Poperboord Export Associotion hos heodquorters in New York, but two of its 12 members ore in the West; thus, o portion of the octivity of this associotion is ossocioted with western wood products.

6/ Informotion about the Douglos Fir Export Co. wos obtained from the compony files, on deposit ot the Oregon Historicol Society, Portland, and o telephone interview with Mr. Bernard K. Fronk of Portlond, former manager of the compony.

Table 5 — **Functions of Webb-Pomerene associations related to the functions actually performed by selected Pacific coast Webb-Pomerene associations**

Function	Level of importance for the company		
	Douglas Fir Export Co.	Pacific Forest Industries	Plywood International
1. Centralize physical distribution of exports, shipping, insurance, etc.	Major	Major	Not a function
2. Employ foreign selling agents through whom members exported to foreign markets	Minor	Major	Not a function
3. Establish uniform price	Major	Major	Major
4. Establish or allocate quotas	Major	Major	Major
5. Establish uniform terms of trade	Minor	Major	Minor
6. Conduct advertising in foreign markets (promotion)	Minor	Major	Minor
7. Distribute information concerning foreign markets	Major	Major	Minor
8. Standardize the product	Minor	Minor	Minor
9. Present a common front against foreign cartels	Not a function	Not a function	Not a function
10. Stabilize credit conditions	Minor	Major	Not a function
11. Reduce warehousing cost through joint storage	Not a function	Major	Not a function
12. Disposal of surplus goods	Not a function	Minor	Not a function

Source: List of functions was obtained from Curry, Robert L., Jr. An economic analysis of the gains from trade effects of Webb-Pomerene export trade associations 1967. (Unpublished Ph.D. thesis on file at Univ. of Oregon Library.) Level of importance was obtained from interviews with company personnel.

The Webb Act was tailormade for Douglas Fir Ex. and Ex., and the company registered as a Webb association shortly after the Act was passed in 1918.

The early membership included most of the largest lumber mills in the Pacific Northwest. By 1918, there were over 50 members, and their combined capacity was 9.5 million board feet per day. The members were stockholders of the association, and each member mill was assigned a certain export quota depending on the extent of its holdings in the association. The association handled all export sales from these mills and, at first, sold through association sales agents overseas or through independent export sales companies. In the early 1920's, the association eliminated its overseas sales operation and sold exclusively

through independent export sales companies.[7/] Thus, from that time on, Douglas Fir Ex. and Ex. acted primarily as an intermediary between sawmills and export merchants. Its major functions were to (table 5):

a. Centralize physical distribution of exports, shipping, insurance, etc.
b. Establish uniform price.
c. Establish or allocate quotas.
d. Distribute information concerning foreign markets.

In 1937, the name of the association was changed to Douglas Fir Export Co.

The association was strong through the 1920's and 1930's. Some members dropped out, but others were signed up and the membership remained fairly steady during this period. Membership began to decrease after World War II as some member firms felt they had become large enough to handle their own export business. Others simply went out of business or decided to sell all of their output in the domestic market. New members were difficult to get because the strong postwar domestic market dampened incentive to export.

Finally, in 1960, with membership down to 11 firms, of which several were not meeting their export quotas, the trustees decided to dissolve the company. Thus, a company, which had had 277 different members over its 47-year history and had been a major factor in establishing Pacific coast wood products in foreign markets, dissolved — just a few years before log exports to Japan grew to over 10 percent of the timber cut in western Oregon and western Washington.

Pacific Forest Industries.—Pacific Forest Industries started operating as a Webb association in 1935.[8/] The main purpose of the association was to promote and sell softwood plywood in foreign markets.

The association had 11 members at its beginning, and throughout its peak years — which included the World War II years — it accounted for a majority of the plywood volume exported from the Pacific coast.

Pacific Forest Industries operated as a direct foreign sales representative. The association had resident sales agents in foreign countries who operated on a commission basis. Orders were taken and export quotas were assigned to members. All orders were for 4- by 8-foot or 4- by 10-foot panels — no special sizes were marketed. Members from California, Oregon, Washington, and British Columbia delivered their export production to a central warehouse at Tacoma from where ships were loaded.

The major markets for the association were Europe (particularly the United Kingdom), Latin America, the Middle East, and the Philippines.

The major functions of the association were to:

a. Centralize physical distribution of exports, shipping, insurance, etc.
b. Employ foreign selling agents through whom members exported to foreign markets.
c. Establish uniform price.
d. Establish or allocate quotas.
e. Establish uniform terms of trade.
f. Conduct advertising in foreign markets (promotion).
g. Distribute information concerning foreign markets.
h. Stabilize credit conditions.
i. Reduce warehousing cost through joint storage.

The association made Webb Act history in 1939 when it was charged with being "in restraint of export trade of domestic competitors." The charge resulted in the first issuance to a Webb association[9/] of Federal Trade Commission recommendations for adjustment of operations. The FTC charged Pacific Forest Industries with:

1. Prohibiting members from selling plywood directly to other American exporters.

7/ Actually, the company maintoined on overseas sales force "for exploitotion only" in countries where Pacific coast wood products did not hove estoblished markets. The countries which were considered to be estoblished markets were: Africo, Australia, Chile, China, Ecuador, India, Jopan, Mexico, New Caledonia, New Zealand, Peru, South Sea Islands, ond oll ports of the United Kingdom.

8/ Information about Pacific Forest Industries wos obtained in a telephone interview with Mr. Harold V. Crooker of Tacoma, o former manager of the association.

9/ Pacific Forest Industries, Ap. 1-13889 (later Docket 202-1), reported in o footnote ot 40 FTC Report 843 (1945).

2. Advertising in foreign countries thot it wos the sole export representative of the plywood mills in the United Stotes Pacific Northwest.

The FTC recommended that the ossociation rewrite its bylaws so thot members could sell to other Americon exporters "without reference to or opproval by the associotion" ond thot the association not try to "fix or impose prices, terms, or conditions of soles to or by American exporters of plywood produced by its members, or take ony other oction designed to prevent or restrict such sales." The FTC olso recommended thot the association stop odvertising thot it wos the sole export representative for Douglos-fir plywood.

The ossociation responded favorobly to the FTC recommendotions and the cose was never referred to the U.S. Attorney Generol.

Pacific Forest Industries wos dissolved in 1964. Three reosons were given for its decline:

1. The expanding Conadion plywood industry took over the ossociotion's big market in the United Kingdom because U.S. plywood foced o 10-percent toriff ond there wos no toriff for Conadian plywood.
2. Japonese hordwood plywood wos being substituted for Douglas-fir plywood in Pacific markets.
3. Most of the big firms thot had been members decided they could do better on their own in export morkets ond thus had no need for cooperoting through the ossociotion.

As in the case of Douglas Fir Export Co., Pocific Forest Industries dissolved just ot the time the Joponese demand for Pocific Northwest wood become very obvious.

Plywood International.—Plywood Internotionol wos begun as o Webb ossociation in 1964 with offices in Tocomo, Wosh. Its purpose wos to engoge in the export of plywood ond other forest products. Specificolly, the bylows provided thot:

> . . . the Boord of Trustees or the Executive Committee is outhorized to represent the export industry in deoling with federol ond locol outhorities in questions pertoining to the export trode; to bring obout uniform ond efficient morketing methods, hondle cloims, ond inform members in regord to foreign morketing ond cooperotive conditions.

The bylows do not provide for Plywood Internotionol to act as o soles agent — this wos on intentional omission. The major functions of the ossociotion as formuloted by its original membership were to set an export market quoto for members ond to determine o price schedule which would set the maximum prices of Plywood International members to export morkets. The ossociotion was also to engage in plywood promotion and stondardization of product ond packaging.[10/]

Plywood Internotional set on export quota of 50,000 square feet, 3/8-inch bosis, per month for each member. The associotion published maximum pricelists and o standord packoging policy for members. However, in February 1967, its membership, then down to 20 from o high of 26, voted that Plywood International "cease to operote until further determination of the membership." Thus, Plywood Internotionol is still registered os o Webb ossociotion but is dormont.

It is difficult to opproise the operotion of Plywood Internotionol. Since it did not operate os o soles ogent, the setting of quotos ond prices wos of questionable value. The members still hod to decide on their own whether they reolly wanted to export and then negotiote the sales through an independent export merchont. How much they sold ond ot whot price wos essentiolly independent of Plywood Internationol influence.

Plywood Internotional did not function in export plywood promotion. The ossociotion wos formed under the auspices of the Americon Plywood Association. Its members were olso APA members. It was the APA thot sent trade missions to Japon to promote plywood and mointained full-time representatives in Jopon and Europe, not Plywood Internotionol. Of course, the reports of these trode missions ond representotives were mode ovoiloble to Plywood Internationol, but Plywood Internotionol was not the driving force behind plywood export promotion.

10/ Information about Plywood Internationol was obtained from Mr. Harold O. Schadt of Tacomo, former octing manager of Plywood Internationol.

Plywood International went dormant because it didn't perform any unique and useful function. Its quotas and price schedules were unenforceable and essentially meaningless. Its attempts to standardize packaging could have been done as well by the American Plywood Association, as was the case with export plywood promotion. In short, the provisions of the Webb Act were not of much use for the export marketing of plywood — this is of particular significance since Plywood International was formed and operated during a period of expanding wood products exports.

IS THE WEBB-POMERENE ACT WORTHWHILE FOR THE WOOD PRODUCTS INDUSTRIES?

Can it be concluded by this analysis that the Webb-Pomerene Act is a dead letter with regard to wood products exports? Perhaps. But if so, it isn't because the Webb Act is inappropriate for the export problems of the wood products industries. Rather, it is because the wood products industries either have better alternatives to the Webb Act for marketing overseas, or the segment of the wood products industries that could benefit is not familiar with the Webb Act, not interested in exporting, or not capable of multifirm cooperation in the formation of a Webb association.

It has already been noted that the wood products industries have been among the more active in the use of the Webb Act. In fact, Webb-assisted exports by the currently active Pulp, Paper, and Paperboard Association accounted for $65.1 million or 14.3 percent of all U.S. exports of pulp, paper, and paperboard in 1962 (Federal Trade Commission 1967, p. 41).

A profile of **active** Webb associations developed by the FTC discloses characteristics that these associations had in common (Federal Trade Commission 1967, pp. 32-34):

1. The member firms produced a homogeneous (nondifferentiated) product.
2. The associations involve firms which are significant factors in their respective domestic and foreign markets.
3. Those associations that acted as sales agents represented firms with **dominant** domestic and world market positions.
4. The associations which were fully functioning (table 5)[11/] were dominated by large firms and were in industries that were highly concentrated suppliers of raw materials, such as chemicals.

It was noted in particular that, of the total of Webb-assisted exports in 1962, 77 percent was by firms located in industries where 50 percent or more of domestic production was accounted for by the leading eight firms (Federal Trade Commission 1967, p. 45). Mead (1964, p. 55) showed that in 1960 the leading eight Pacific coast lumber firms produced about 20 percent of the Pacific coast lumber output. When the lumber industry for the Nation as a whole is considered, the eight largest firms account for only 13 percent of the production.

Thus, with a nondifferentiated product like lumber or plywood, the wood products industries seemingly have the potential for successful Webb affiliation. However, with regard to the lumber industry, the lack of concentration in production is a factor against successful Webb affiliation. It should be noted that Douglas Fir Export Co. and Pacific Forest Industries prospered mainly during the period that they represented a majority of the production in their respective industries — and faltered when the larger companies dropped their membership. This is ironic in that the Webb Act was designed primarily for the benefit of small firms in export trade.

A conclusion based on the above analysis is that if successful Webb affiliation does inevitably depend on membership by the large firms representing a large portion of the industry output, then it is not likely that a successful Webb association could be formed in either the Pacific coast lumber or plywood industries. In both industries, the larger

11/ Performing all or nearly all of the functions conducted by any Webb association.

firms ore olreody independent exporters. A Webb ossociation which would only represent competition to their existing export morketing system is not likely to be encouroged.

If, however, the theory ond intent of the Webb Act is volid, there moy be o potentiol for o successful Webb ossociation for the Pocific coast wood products industries exclusive of the larger firms. At present, wood products firms hove the opportunity to export through export merchonts — either independent troding componies or one of the lorge firms in the industry thot hos an exporting function. It is up to the firm to decide to export ond then to work with the export merchont to orrive ot sotisfoctory morketing orrongements. If this olternotive is sotisfoctory to the industry os o whole ond if everyone thot wonts to export is being odequotely served with regard to export morketing orrongements, price, etc., then there is no need for o Webb associotion. A Webb ossociotion is on olternotive thot should be considered only if the obove arrangements ore not entirely sotisfoctory.

It is conceivoble thot a number of wood products firms that ore not now in the export morket, or who just dobble in it, could collectively decide to give up all or a portion of their position in the domestic morket in fovor of an intensive effort in overseas markets. If they corefully ossess the export morket potential and the competition from other exporters, both U.S. ond non-U.S., ond decide thot they can compete, there is every reoson to believe thot their potentiol success con be enhonced by forming o Webb ossociation. In fact, the formotion of a Webb associotion is o logicol first step just to determine who will be on the teom ond how teom membership will influence the obility to compete.

The success of such on ossociotion, other things being equol, would depend on:

1. A membership committed to the export market with volumes lorge enough to handle typicol foreign orders.
2. A competent ossociotion monogement thot is aggressive os o selling ogent or os on intermediory between mills and exporting merchonts ond is knowledgeoble obout the intricocies of foreign trode.

The functions performed by such an association would depend on the desires of the membership; but to be useful, the ossociotion must have some productive functions which would be impossible or less efficient under ony olternotive export morketing orrongement. One obvious function in this cotegory is price setting.[12/]

12/ One difficulty in foreign trode of wood products hos been frequent export price fluctuations which ore reloted to price chonges in the domestic morkets. Exporters tend to hove more success if they stobilize export prices — o very good possibility under Webb offiliotion.

SUMMARY

The Webb Act wos spowned during a period of uncertointy with regard to the obility of U.S. firms to compete in world trode. In the ensuing 50 yeors, the United Stotes hos become very successful in world trade, with very little of this success ottributoble to the existence of the Webb Act. Recent study of the Webb Act by the Federol Trode Commission hos prompted the following comment (Federol Trode Commission 1967, p. 69):

> A combination of estoblished administrative precedents as well as changing canditians in world trade provide a basis for recammending that Congress clarify its intent with respect to the Webb-Pamerene Act. In particular it is recommended that Webb-Pomerene exemptians be limited ta firms thot con demonstrote need.

This recommendation arises from the irony that the Webb Act, which wos designed to assist small firms, hos benefited mostly lorge firms that didn't reolly need the provisions of the Act in the first place.

It is o significont foct that the wood products industries hove been among the more octive users of the Webb Act. However, even omong the wood products Webb ossociotions, success hos been reloted to the porticipotion of lorge firms. For example, the Douglos Fir Export Co. ond Pocific Forest Industries flourished only while the lorger firms were members ond foltered when these large

firms dropped out. Also, the currently active Pulp, Paper, and Paperboard Association has the Nation's largest paper firms among its members.

The need for and benefits of a Webb-Pomerene association in the Pacific coast lumber and plywood industries are conjectural, but the Webb-Pomerene Act does provide an alternative export marketing arrangement which can have some unique functions.

In the quest for expanded trade in finished wood products with Japan and other countries, the possibilities of Webb-Pomerene associations should not be overlooked.

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Headquarters for the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is in Portland, Oregon. The Station's mission is to provide the scientific knowledge, technology, and alternatives for management, use, and protection of forest, range, and related environments for present and future generations. The area of research encompasses Alaska, Washington, and Oregon, with some projects including California, Hawaii, the Western States, or the Nation. Project headquarters are at:

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MECHANICS OF RUNNING SKYLINES

by

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Portland, Oregon

U.S.D.A. Forest Service
Research Paper PNW-75
1969

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1.0 INTRODUCTION

In April 1967, the running skyline system was presented.[1] Since then, several running skyline units have been developed for yarding partial and clear cuts. Their success indicates that they may achieve increasing acceptance by all concerned with efficient logging and improved forest practices. Because of the importance of running skylines, it is timely to present a description of the various systems and procedures for determining their payload capability. These procedures are presented in the form of worksheets to simplify solutions. They are intended primarily as a practical tool for those who plan running skyline operations. The mathematical derivation of the procedures is included for those interested in a full understanding of the mechanics of running skylines.

[1] Lysons, Hilton H., and Mann, Charles N. Single-span running skylines. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Res. Note PNW-52, 7 pp., illus. 1967.

A standing skyline employs a fixed or standing line for support of the load and additional lines for movement and control. The running skyline system eliminates the need for a standing line. Figure 1(1) shows the essential elements of the running skyline. As the name "running skyline" implies, the traveling lines provide lift and movement to the suspended load. The main and haulback drums are interlocked in a manner that maintains relatively constant tensions at any position of the lines. Since two lines support the load, they can be smaller than a single line for the same load.

A feature of the running skyline system is that it adjusts itself to the weight of the load; i.e., the deflection increases with heavier loads to provide lift to the suspended load without adding to the line tensions.

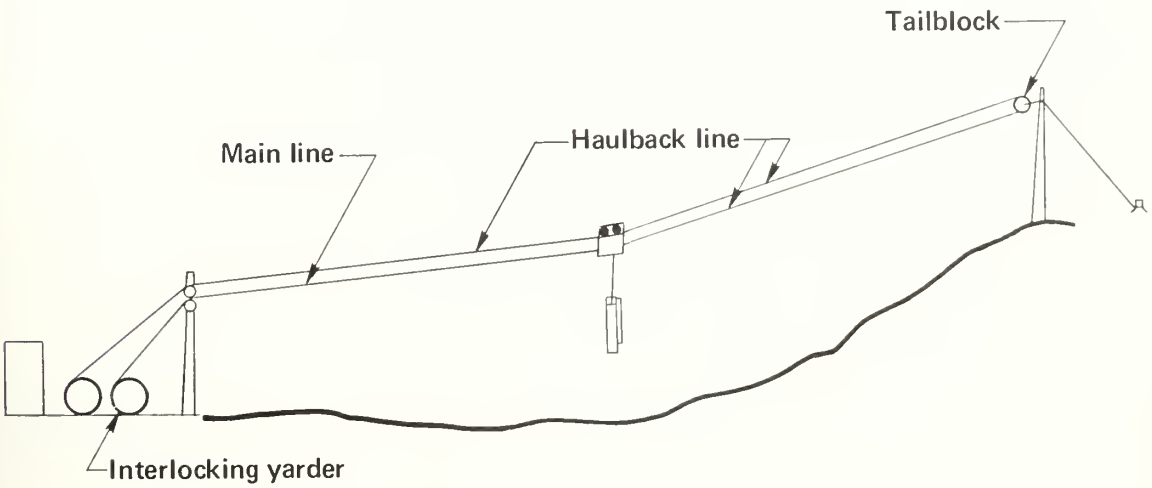


Figure 1(1).--Running skyline system.

2.0 SYSTEMS IN USE

Running skylines have been used in the Pacific Northwest with grapples and skyline-crane carriages. Yarding distance capability presently approximates high-lead equipment, but indications are that larger cable drums will be made available to greatly extend this distance. The grapple system, which is limited to clearcut operations, requires a two-man crew as compared to five or six men on a typical high-lead operation. High mobility is one of the principal design features of running skyline systems.

A typical running skyline-crane carriage is shown in figure 2(1). The third line shown is used to pull slack in the main line as needed to reach the load. Carriages of this type have been used both as skyline cranes and with grapples. When used with a grapple, the slack-pulling line, which reeves through the carriage, functions as the grapple-opening line, as shown in figure 2(2). Grapples requiring only main and haulback lines for operation have also been used with the running skyline. One grapple of this type cycles to open and close. Another uses electronics and an independent power source for operation.

In the running skyline analysis which follows, the system payload capability is based on the safe working load of the lines when the load is suspended directly below the carriage. However, it is important to be aware of other situations which can impose high stresses on the lines. If the log is on the ground between the carriage and the tailblock when the lines are tensioned, as shown in figure 2(3), tension in the main line is increased until enough force is applied to move the log. For this condition, tension in the haulback line is less than in the main line. A more serious situation is encountered when the lines are tensioned with the log on the ground between the yarder and the carriage, as shown in figure 2(4). Again, the main line tension is increased until enough force is applied to move the log. However, in this case the main line imposes a block purchase on the haulback line. In an extreme condition, tension in the haulback line can approach twice that in the main line. Therefore, this yarding situation should be avoided whenever possible.

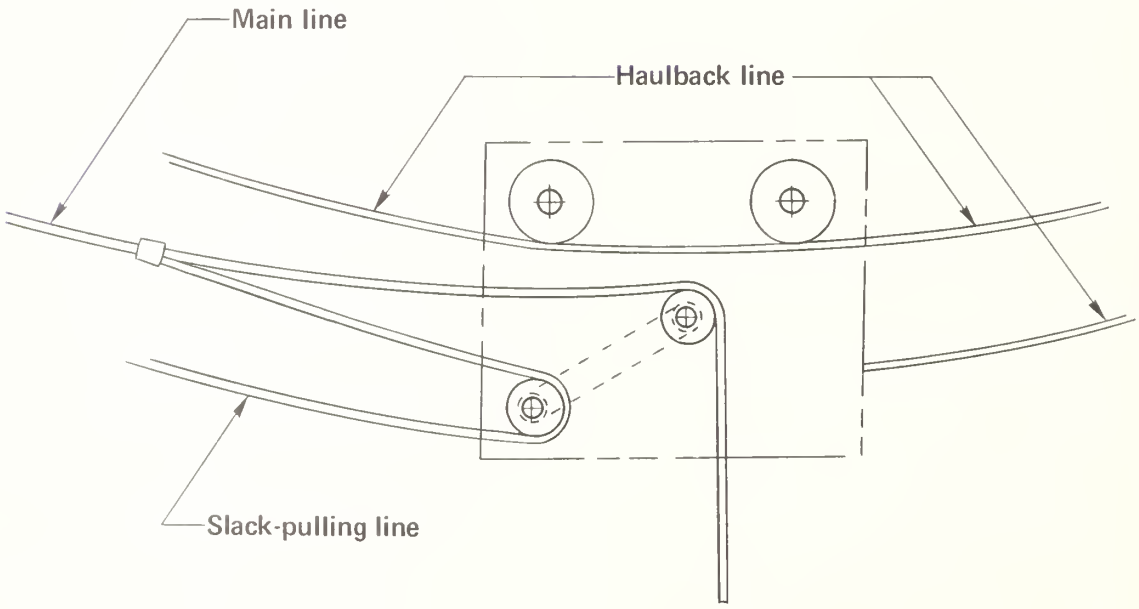


Figure 2(1).--Running skyline slack-pulling carriage.

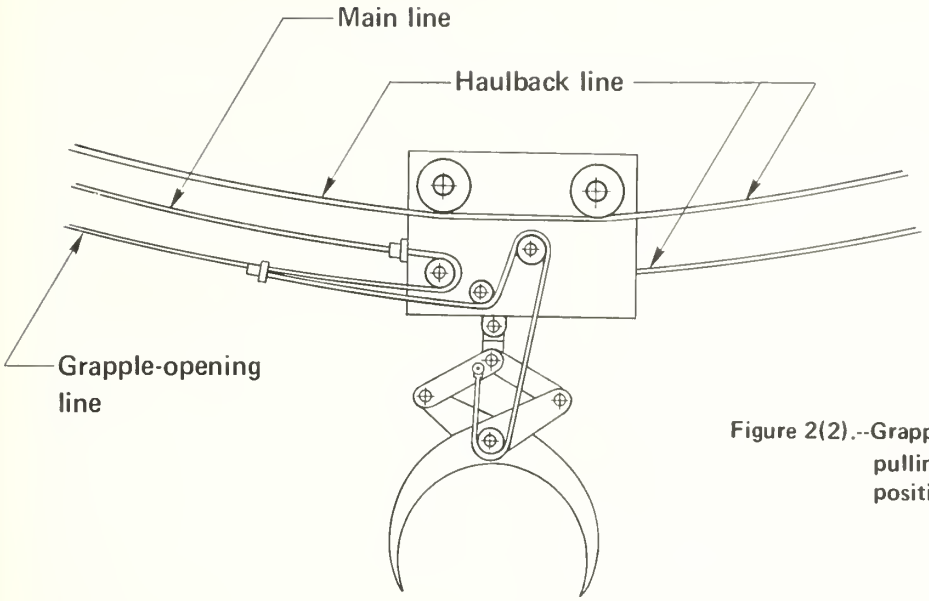


Figure 2(2).--Grapple attached to slack-pulling carriage (open position).

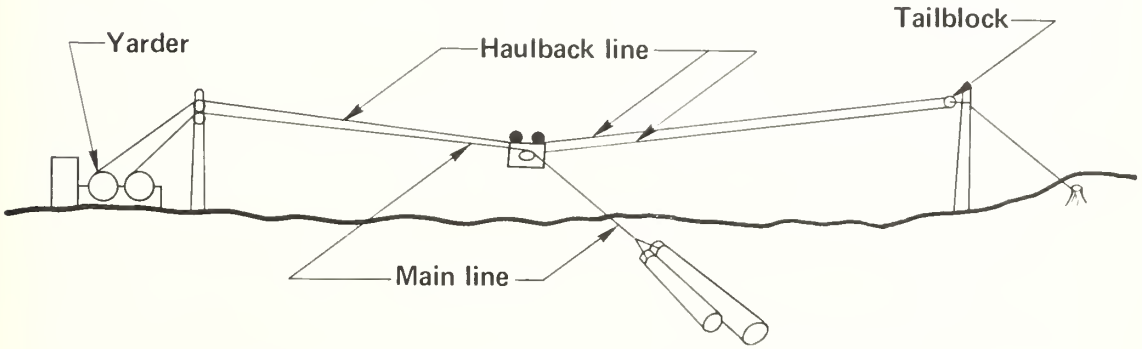


Figure 2(3).--Lines tensioned with log between tailblock and carriage.

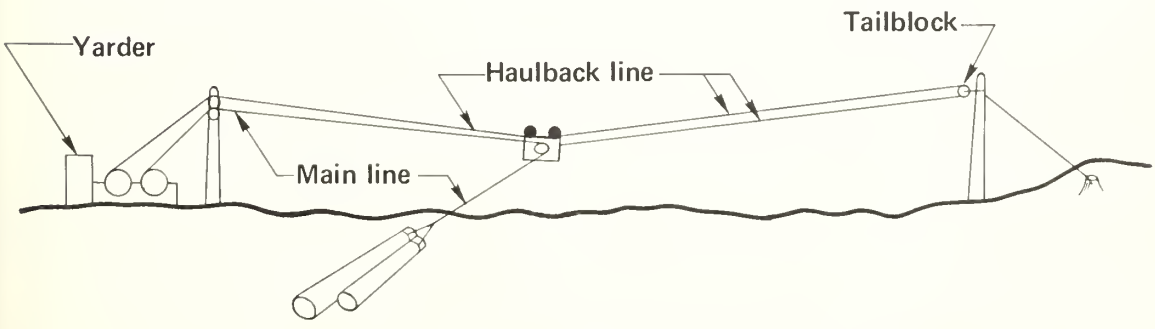


Figure 2(4).--Lines tensioned with log between yarder and carriage.

3.0 RUNNING SKYLINE ANALYSIS

This analysis is based on use of coefficients in the "Skyline Tension and Deflection Handbook"[2] for standing skylines. The approach used here is the same as that in the handbook. System capability is based on analysis of the running skyline in a static condition with the load at midspan. Tension in the lines is separated into tension due to the load and tension due to cable weight.

$$T = T_C + T_L$$

where: T is the total tension, T_C is the tension due to cable weight, and T_L is the tension due to load.

The tension due to cable weight is a function of unit cable weight, span length, and deflection, and can be found by use of methods described in the handbook. Therefore, this portion of the analysis is concerned only with the tension due to load. The problem here is to determine how the load is supported by the lines and how coefficients in the handbook can be related to the running skyline system. The following coefficients are tabulated in the handbook:

a. Coefficient (A)--tension due to cable weight – kips/station/pound of cable weight/foot – figure 11 or table 2

b. Coefficient (B)--tension due to load, carriage not clamped to skyline – kips/kip – figure 12 or table 3

c. Coefficient (C)--tension due to load, carriage clamped to skyline – kips/kip – figure 13 or table 4

[2] Lysons, Hilton H., and Mann, Charles N. Skyline tension and deflection handbook. Pacific Northwest Forest & Range Exp. Sta. U.S.D.A. Forest Serv. Res. Pap. PNW-39, 41 pp., illus. 1967.

The problem of determining tensions in the lines due to load can be solved by analysis of the system with weightless lines. Figure 3(1) shows a free body diagram of the running skyline carriage with weightless lines. This diagram represents both the single main line systems and those employing a main line plus a line for pulling slack or opening grapples. Since only the main line supports the load, the slack-pulling or opening line is ignored in the analysis.

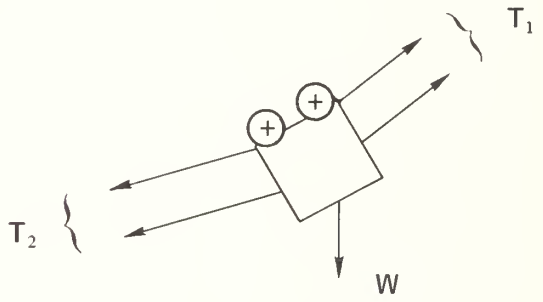


Figure 3(1).--Free body diagram of running skyline carriage. T_1 and T_2 are tension in the upper lines and tension in the lower lines due to load, and W is the weight of the carriage and the logs.

Figure 3(2) shows a force diagram of the weightless line system with the tensions combined into single vectors. This force diagram is also that

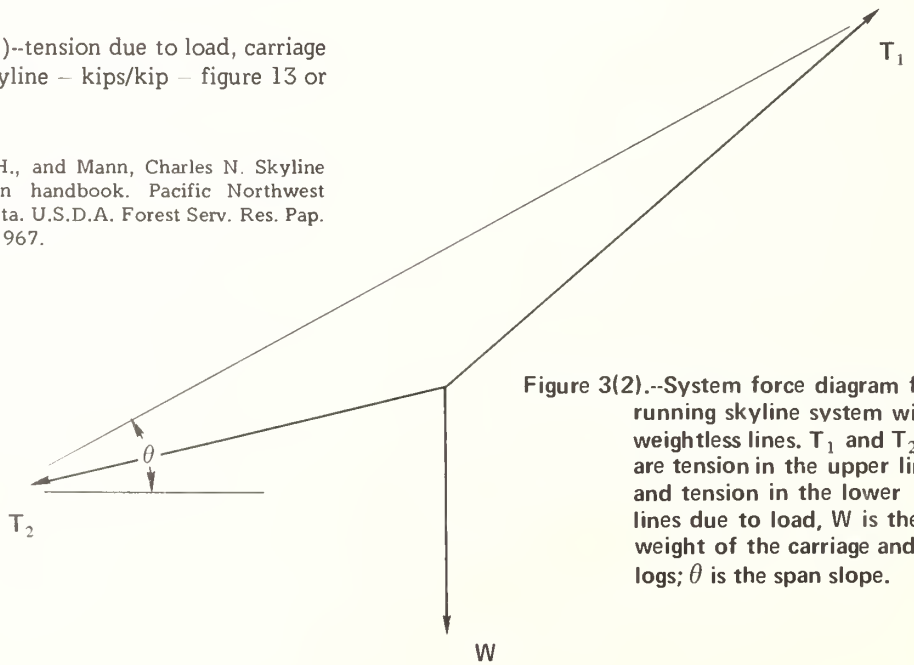


Figure 3(2).--System force diagram for running skyline system with weightless lines. T_1 and T_2 are tension in the upper lines and tension in the lower lines due to load, W is the weight of the carriage and logs; θ is the span slope.

of a single weightless line system with the carriage clamped to the skyline. Therefore, the tension in the upper lines due to load is the same as that with a clamped carriage. That is,

$$T_1 = W(C)$$

Now consider the force diagram of a weightless line system with the same load and a carriage which does not clamp to the skyline. This is shown in figure 3(3). In this case, the skyline supports only the component of load normal to the chord of the skyline, which is the vector component W cos θ. The snubbing force, W sin θ, is provided by an auxiliary line. Tension in the upper line is reduced vectorially by W sin θ, and tensions in the upper line and the lower line due to load are equal to T_2. Therefore, the tension in the lower lines due to load in the running skyline is the same as that in a system with a nonclamping carriage. That is,

$$T_2 = W(B)$$

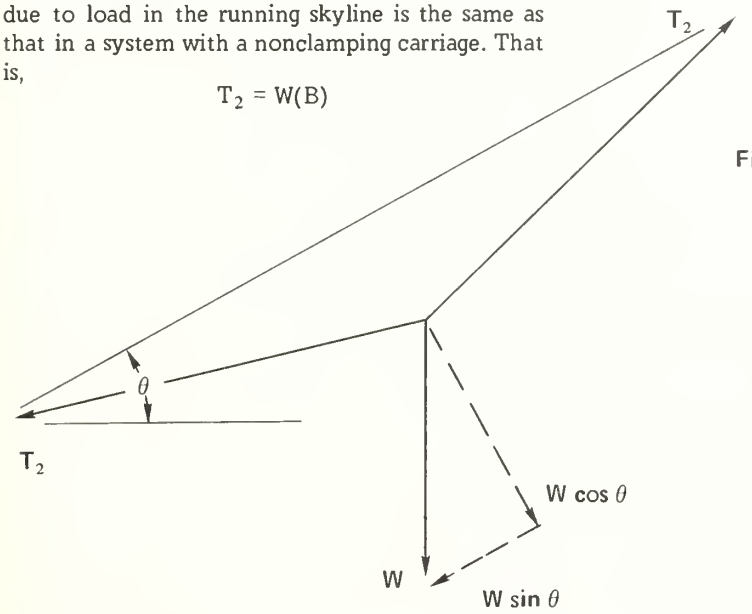


Figure 3(3).--System force diagram for weightless line skyline system with nonclamping carriage. T_2 is the tension in the skyline, W is the weight of the carriage and logs, and θ is the span slope. W cos θ is the component of load supported by the skyline and W sin θ is the component of load supported by a snubbing line.

It is necessary now to determine how these values of tension due to load are supported by the lines of the running skyline. Loading of the lines depends on whether the yarder is at the lower or the upper end, and these conditions must be treated separately.

3.1 SYSTEM WITH YARDER AT UPPER END

This configuration is shown in figure 3(4). H_1, H_2, and H_3 are the tensions in the haulback line due to load; M is the tension in the main line due to load; and W is the weight of the carriage and the logs.

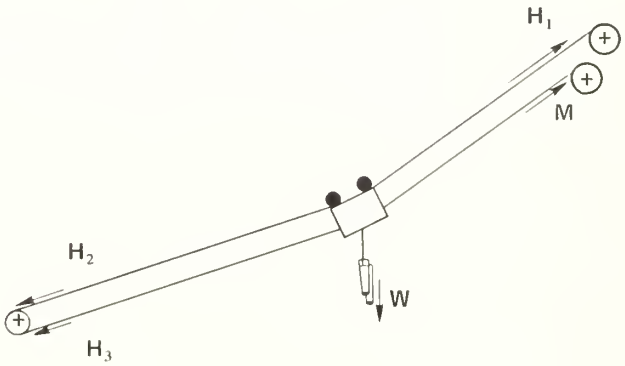


Figure 3(4).--Weightless line running skyline system with yarder at upper end. H_1, H_2, and H_3 are the tensions due to load in the haulback line segments, M is the tension due to load in the mainline, and W is the weight of the carriage and logs.

Tension due to load in the haulback is equal in the three segments,

$$H_1 = H_2 = H_3,$$

and,

$$T_2 = H_2 + H_3 = W(B)$$

The tension in the haulback due to load then is,

$$H_1 = \frac{W}{2}(B)$$

For the upper lines,

$$T_1 = H_1 + M,$$

$$CW = \frac{W}{2}(B) + M$$

Tension in the main line due to load, therefore, is,

$$M = \frac{W}{2}(2C\text{-}B).$$

3.2 SYSTEMS WITH YARDER AT LOWER END

This arrangement is shown in figure 3(5).

Again, tension in the three segments of the haulback is equal,

$$H_1 = H_2 = H_3,$$

and,

$$T_1 = H_2 + H_3 = W(C)$$

Tension in the haulback due to load then is,

$$H_2 = \frac{W}{2}(C)$$

Considering the lower lines,

$$T_2 = H_1 + M,$$

$$BW = \frac{W}{2}(C) + M$$

Tension in the main line due to load, therefore, is

$$M = \frac{W}{2}(2B\text{-}C)$$

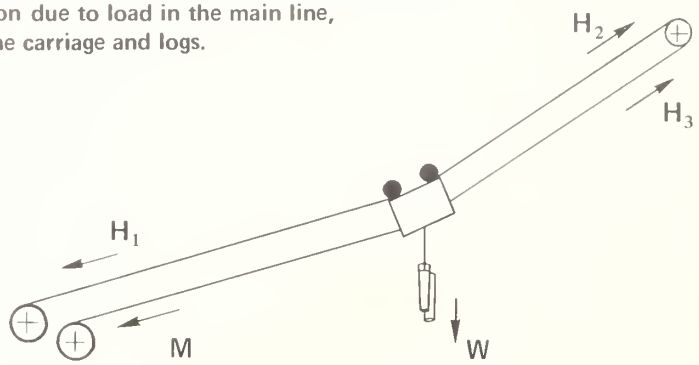
This analysis can now be applied to find the capability of the systems.

4.0 CAPABILITY

The system payload capability of running skylines can be determined from the graphical techniques and coefficients in the skyline handbook (see footnote 2) and the worksheets included in this research paper. The handbook may be obtained from Director, Pacific Northwest Forest and Range Experiment Station, P. O. Box 3141, Portland, Oregon 97208. The worksheets included in this research paper replace those in the footnote 1 reference.

The load path of the standing skyline is used for the running skyline analysis. This is a conservative approximation, but it is the only practical method available short of a computer analysis for each condition. The analysis on the worksheets is based on finding the capabilities of the main line and the haulback line separately. The smaller of the two payload capabilities is the capability of the system. This means that one of the lines must be operated at less than its allowable tension.

Figure 3(5).--Weightless line running skyline system with yarder at lower end. H_1, H_2, and H_3 are the tensions due to load in the haulback line segments, M is the tension due to load in the main line, and W is the weight of the carriage and logs.



The handbook analysis of single-span standing skylines results in payload capability based on the maximum safe working cable tension at the upper end of the span. When the handbook coefficients are applied to the running skyline system, a correct solution results for the case of the yarder at the upper end since both lines terminate at the upper end of the span. However, for the case of the yarder at the lower end, the main line does not extend to the upper end, and results based on this line are conservative since the reduction in tension due to elevation is neglected.

System payload capability is the maximum allowable vertical force that can be applied to the carriage. This corresponds to the weight of logs which can be carried free of the ground. Payload capability, when one end of the load is allowed to drag on the ground, depends on the slope, coefficient of friction, and log weight. Analysis of the condition with one end of the load allowed to drag is beyond the scope of this paper. If the main line is reeved through the carriage, the payload capability cannot exceed the main line safe working load.

Use of the worksheets for each yarder position is discussed below.

4.1 SYSTEM WITH YARDER AT UPPER END--Fig. 4(1)

In this case, the main line provides the snubbing force. If the lines are the same size, analysis of the main line capability will give the system capability. Detailed steps are listed below:

a. Make a plot of the skyline profile by following the procedures given in the "Skyline Tension and Deflection Handbook" and determine the allowable loaded deflection, the horizontal span length, and the slope of the span.

b. Obtain the required coefficients from the handbook, enter the carriage weight, and calculate the capability based on the main line. If the haulback line is the same size as the main line, the capability based on the main line is the system capability.

c. For systems with lines of different sizes, continue on the worksheet and determine the haulback line capability. System payload capability is the lower of the two capabilities.

4.2 SYSTEM WITH YARDER AT LOWER END--Fig. 4(2)

For this configuration, the haulback line provides the snubbing force, and system capability is based on this line if both lines are the same size. Steps on the worksheet are the same as those for the yarder at the upper end except the haulback line analysis is performed first.

4.3 RUNNING SKYLINE EXAMPLES

A profile plot of a proposed skyline road yields the following information:

Horizontal span length	800 feet
Slope of span	40 percent
Allowable loaded deflection	10 percent

It is assumed that there is suitable access at the upper and lower ends of the skyline road, and that the yarder is equipped with 3/4-inch-diameter, extra-improved, plow steel main and haulback lines.

Figures 4.3(1) and 4.3(2) show examples of the applications of the sample worksheets (figs. 4(1) and 4(2)) in calculating the system's payload capabilities for either uphill or downhill yarding under the conditions given. Note that where the main and haulback lines are the same diameter, it is not necessary to calculate the capabilities of both lines to determine the system's capabilities.

Unit No._____
Skyline Road No._____

DETERMINE FROM SKYLINE PROFILE

Allowable loaded deflection	_____	percent
Horizontal span length (one station = 100 feet)	_____	stations
Slope of span	_____	percent

OBTAIN COEFFICIENTS FROM "SKYLINE TENSION AND DEFLECTION HANDBOOK"

Coefficient A (fig. 11 or table 2) kip/sta./lb./ft.	_____	
Coefficient B (fig. 12 or table 3)	_____	kip/kip
Coefficient C (fig. 13 or table 4)	_____	kip/kip
Coefficient D (2 x coeff. C _____ - coeff. B _____)	_____	kip/kip

CARRIAGE WEIGHT (1 kip = 1,000 pounds) _____ kips

MAIN LINE ANALYSIS:

Specifications: Diameter _____ inches, Weight _____ pounds/foot
Breaking strength _____ kips, Factor of safety _____
Safe working load _____ kips (or maximum yarder line pull)

MAIN LINE CAPABILITY:

Safe working load	_____	kips
Subtract (coeff. A _____ x _____ stations x _____ pounds/foot)	- _____	kips
Remaining payload capability (R.P.C.)	_____	kips
Main line gross capability = $\frac{\text{R.P.C. } \_\_\_\_\_ \text{ kips x } 2}{\text{Coeff. D } \_\_\_\_\_}$	= _____	kips
Subtract carriage weight	- _____	kips
Main line payload capability	_____	kips

If main and haulback are the same size, this is system capability)

HAULBACK LINE ANALYSIS:

Specifications: Diameter _____ inches, Weight _____ pounds/foot
Breaking strength _____ kips, Factor of safety _____
Safe working load _____ kips (or maximum yarder line pull)

HAULBACK LINE CAPABILITY:

Safe working load	_____	kips
Subtract (coeff. A _____ x _____ stations x _____ pounds/foot)	- _____	kips
Remaining payload capability (R.P.C.)	_____	kips
Haulback line gross capability = $\frac{\text{R.P.C. } \_\_\_\_\_ \text{ kips x } 2}{\text{Coeff. B } \_\_\_\_\_}$	= _____	kips
Subtract carriage weight	- _____	kips
Haulback payload capability	_____	kips

SYSTEM PAYLOAD CAPABILITY*

*System payload is the lower of the main line or the haulback capability.

Figure 4(1).--Running skyline worksheet (yarder at upper end).

Unit No._____
Skyline Road No._____

DETERMINE FROM SKYLINE PROFILE

Allowable loaded deflection	_____	percent
Horizontal span length (one station = 100 feet)	_____	stations
Slope of span	_____	percent

OBTAIN COEFFICIENTS FROM "SKYLINE TENSION AND DEFLECTION HANDBOOK"

Coefficient A (fig. 11 or table 2) kip/sta./lb./ft.	_____	
Coefficient B (fig. 12 or table 3)	_____	kip/kip
Coefficient C (fig. 13 or table 4)	_____	kip/kip
Coefficient D (2 x coeff. B _____ - coeff. C _____)	_____	kip/kip

CARRIAGE WEIGHT (1 kip = 1,000 pounds) _____ kips

HAULBACK LINE ANALYSIS:

Specifications: Diameter _____ inches, Weight _____ pounds/foot
Breaking strength _____ kips, Factor of safety _____
Safe working load _____ kips (or maximum yarder line pull)

HAULBACK LINE CAPABILITY:

Safe working load	_____	kips
Subtract (coeff. A _____ x _____ stations x _____ pounds/foot) -	_____	kips
Remaining payload capability R.P.C.)	_____	kips
Haulback gross capability = $\frac{\text{R.P.C. } \_\_\_\_\_ \text{ kips} \times 2}{\text{Coeff. C } \_\_\_\_\_}$	_____	kips
Subtract carriage weight	- _____	kips
Haulback line payload capability	_____	kips

(If main and haulback are the same size, this is system capability)

MAIN LINE ANALYSIS:

Specifications: Diameter _____ inches, Weight _____ pounds/foot
Breaking strength _____ kips, Factor of safety _____
Safe working load _____ kips (or maximum yarder line pull)

MAIN LINE CAPABILITY:

Safe working load	_____	kips
Subtract (coeff. A _____ x _____ stations x _____ pounds/foot) -	_____	kips
Remaining payload capability (R.P.C.)	_____	kips
Main line gross capability = $\frac{\text{R.P.C. } \_\_\_\_\_ \text{ kips} \times 2}{\text{Coeff. D } \_\_\_\_\_}$	_____	kips
Subtract carriage weight	- _____	kips
Main line payload capability	_____	kips

SYSTEM PAYLOAD CAPABILITY* _____ kips

*System payload is the lower of the main line or the haulback capability.

Figure 4(2).--Running skyline worksheet (yarder at lower end).

Unit No._____
Skyline Road No._____

DETERMINE FROM SKYLINE PROFILE

Allowable loaded deflection	10	percent
Horizontal span length (one station = 100 feet)	8	stations
Slope of span	40	percent

OBTAIN COEFFICIENTS FROM "SKYLINE TENSION AND DEFLECTION HANDBOOK"

Coefficient A (fig. 11 or table 2) kip/sta./lb./ft.	0.176	
Coefficient B (fig. 12 or table 3)	2.54	kip/kip
Coefficient C (fig. 13 or table 4)	2.91	kip/kip
Coefficient D (2 x coeff. C 2.91 - coeff. B 2.54)	3.28	kip/kip

CARRIAGE WEIGHT (1 kip = 1,000 pounds) 0.5 kips

MAIN LINE ANALYSIS:

Specifications: Diameter 3/4 inches, Weight 1.04 pounds/foot
Breaking strength 58.8 kips, Factor of safety 3
Safe working load 19.6 kips (or maximum yarder line pull)

MAIN LINE CAPABILITY:

Safe working load	19.60	kips
Subtract (coeff. A 0.176 x 8 stations x 1.04 pounds/foot)	- 1.46	kips
Remaining payload capability (R.P.C.)	18.14	kips
Main line gross capability = R.P.C. 18.14 kips x 2 / Coeff. D 3.28	11.06	kips
Subtract carriage weight	- 0.5	kips
Main line payload capability	10.56	kips

(If main and haulback are the same size, this is system capability)

HAULBACK LINE ANALYSIS:

Specifications: Diameter 3/4 inches, Weight 1.04 pounds/foot
Breaking strength 58.8 kips, Factor of safety 3
Safe working load 19.6 kips (or maximum yarder line pull)

HAULBACK LINE CAPABILITY:

Safe working load	19.60	kips
Subtract (coeff. A 0.176 x 8 stations x 1.04 pounds/foot)	- 1.46	kips
Remaining payload capability (R.P.C.)	18.14	kips
Haulback line gross capability = R.P.C. 18.14 kips x 2 / Coeff. B 2.54	14.28	kips
Subtract carriage weight	- 0.5	kips
Haulback payload capability	13.78	kips

SYSTEM PAYLOAD CAPABILITY* 10.56 kips

*System payload is the lower of the main line or the haulback capability.

Figure 4.3(1).--Running skyline worksheet (yarder at upper end).

Unit No. _____
Skyline Road No. _____

DETERMINE FROM SKYLINE PROFILE

Allowable loaded deflection	10	percent
Horizontal span length (one station = 100 feet)	8	stations
Slope of span	40	percent

OBTAIN COEFFICIENTS FROM "SKYLINE TENSION AND DEFLECTION HANDBOOK"

Coefficient A (fig. 11 or table 2) kip/sta./lb./ft.	0.176	
Coefficient B (fig. 12 or table 3)	2.54	kip/kip
Coefficient C (fig. 13 or table 4)	2.91	kip/kip
Coefficient D (2 x coeff. B 2.54 - coeff. C 2.91)	2.17	kip/kip

CARRIAGE WEIGHT (1 kip = 1,000 pounds) 0.5 kips

HAULBACK LINE ANALYSIS:

Specifications: Diameter 3/4 inches, Weight 1.04 pounds/foot
Breaking strength 58.8 kips, Factor of safety 3
Safe working load 19.6 kips (or maximum yarder line pull)

HAULBACK LINE CAPABILITY:

Safe working load	19.60	kips
Subtract (coeff. A 0.176 x 8 stations x 1.04 pounds/foot)	- 1.46	kips
Remaining payload capability (R.P.C.)	18.14	kips
Haulback gross capability = R.P.C. 18.14 kips x 2 / Coeff. C 2.91	12.47	kips
Subtract carriage weight	- 0.50	kips
Haulback line payload capability	11.97	kips

(If main and haulback are the same size, this is system capability)

MAIN LINE ANALYSIS:

Specifications: Diameter 3/4 inches, Weight 1.04 pounds/foot
Breaking strength 58.8 kips, Factor of safety 3
Safe working load 19.6 kips (or maximum yarder line pull)

MAIN LINE CAPABILITY:

Safe working load	19.60	kips
Subtract (coeff. A 0.176 x 8 stations x 1.04 pounds/foot)	- 1.46	kips
Remaining payload capability (R.P.C.)	18.14	kips
Main line gross capability = R.P.C. 18.14 kips x 2 / Coeff. D 2.17	16.72	kips
Subtract carriage weight	- 0.50	kips
Main line payload capability	16.22	kips

SYSTEM PAYLOAD CAPABILITY* 11.97 kips

*System payload is the lower of the main line or the haulback capability.

Figure 4.3(2).--Running skyline worksheet (yarder at lower end).

Mann, Charles N.

1969. Mechanics of running skylines. U.S.D.A. Forest Serv. Res. Pap. PNW-75, 11 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

Presents a general description of running skyline systems and easy-to-use procedures for determining the payload capability of any configuration. Intended primarily as a practical tool for those who plan running skyline operations. Included is a mathematical derivation of the procedures as presented on the worksheets for those interested in a full understanding of the mechanics of running skylines.

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NITROGEN ENRICHMENT OF TWO FOREST ECOSYSTEMS BY RED ALDER

BY

ROBERT F. TARRANT, K. C. LU,
W. B. BOLLEN, AND J. F. FRANKLIN

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RESEARCH PAPER PNW-76
PORTLAND, OREGON 1969

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SUMMARY

Litterfall weight and N content was determined in forest stands of (1) red alder (*Alnus rubra*), a tree capable of symbiotic fixation of atmospheric N; (2) conifers *Pseudotsuga menziesii*, *Tsuga heterophylla*, and *Picea sitchensis*; and (3) a mixture of alder and conifers. Chemical properties were determined for soil and for throughfall precipitation. All trees grew on a Sol Brun Acide soil, derived largely from Eocene siltstone.

Between-stand relationships were alder > mixed > conifer for N (percent of dry weight) in litterfall and precipitation and for N (pounds per acre) in soil and precipitation; alder = mixed > conifer for N weight in litterfall; and conifer > alder = mixed for C:N ratio of litter. Soil N (pounds per acre) to 36 inches was: alder, 16,680; mixed stand, 12,640; and conifer, 11,720.

Weight of N (pounds per acre per year) cycled in litterfall was: mixed stand, 104; alder, 100; and conifer, 32. Current net accretion to N capital of the site in litterfall and throughfall precipitation—attributed to N fixation by alder—was, for the mixed and alder forest types, respectively, 74 and 70 pounds per acre per year.

In the coastal Oregon study area, where soil N is perhaps near the maximum attainable in a forest environment, presence of red alder led to a threefold increase in the amount of N circulating in the ecosystem.

INTRODUCTION

Red alder (*Alnus rubra Bong.*) is a nonleguminous, nitrogen-fixing woody plant and the major hardwood tree species in the Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) region of the Pacific Northwest. Information on the soil-improving function of red alder and other members of its genus has been summarized (Tarrant 1964),[1] and results of a number of recent investigations have been reported for red alder and several other species of *Alnus* (Trappe et al. 1968).

Nitrogen is of special interest in connection with forest soil fertility in the Pacific Northwest because it is the only nutrient element thus far found to appreciably stimulate growth of Douglas-fir when applied as fertilizer (Gessel et al. 1965). The carbon to nitrogen ratio is also important because it is one measure of the potential rate at which N and other nutrient elements in litterfall will be released and made available for use by plants.

As part of an investigation[2] of the effects of red alder on forest soil fertility, we report herein results of a 3-year comparison of litterfall beneath stands of red alder; conifers — Douglas-fir, Sitka spruce (*Picea sitchensis* (Bong.) Carr.), and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.); and a mixture of alder and conifers. Seasonal amounts of litterfall have been determined and quality of litterfall from the different forest types has been assessed as to total nitrogen concentration, total nitrogen weight, and carbon-nitrogen ratio.

We asked in this study: "What is the seasonal and yearly weight of litterfall beneath the three stands? What is the concentration of total N in the litterfall? What is the weight of total N returned to the soil seasonally and yearly beneath these stands? Is the C:N ratio of litterfall different between the several forest types?"

---

[1] Names and dates in parentheses refer to Literature Cited, p 7.

[2] This study was supported in part by the National Science Foundation, Grant No. GB-3214.

STUDY METHODS

The study was conducted at the Station's Cascade Head Experimental Forest on the Oregon coast at latitude 45°3′ N., longitude 123°55′ W. Here, experimental plots were established during 1935-37 to compare growth of pure red alder, pure conifer, and a natural mixed stand of red alder and conifers. The area occupied by the plots was formerly agricultural land which was abandoned about 1925.

Trees on the plots are now about 40 years old and occupy the following basal area (square feet per acre): alders, 156; conifers, 268; and mixed stand, 221. Soils beneath all three stands are Sols Bruns Acides, developed on a deeply weathered, tuffaceous siltstone of Eocene epoch. Detailed morphological and chemical characteristics of the soils are described by Franklin et al. (1968).

In June 1964, 15 ¼-milacre litter traps were placed in each stand. Traps were located in five groups of three each around randomly selected, previously numbered trees on each plot. Distance and direction of the traps from the trees were also determined by random selection.

Litterfall, defined as all plant material falling on the sampling areas, was collected from the traps at 3-month intervals—June-August, September-November, December-February, and March-May. These collection periods are hereinafter referred to, respectively, as "summer," "autumn," "winter," and "spring."

Immediately after the litterfall was collected, it was ovendried to constant weight at 70°C. and weighed to the nearest 0.1 gram. Samples were then analyzed for total N by the Kjeldahl method (Association of Official Agricultural Chemists 1960), and for carbon by use of a medium temperature resistance furnace after the method of Allison et al. (1964).

RESULTS

Litterfall Weight

The mixed stand contained 860 trees per acre, appreciably more than either conifer (490 per acre) or alder (381 per acre) stands. The mixed stand also generated the greatest weight of litterfall per year (5,930 pounds per acre per year) (table 1). Conifer and alder stands produced almost equal amounts of litterfall (4,232 and 4,490 pounds per acre per year) which was only about three-fourths that in the mixed stand.

TABLE 1.—*Litterfall weight by forest type, year, and season of sampling, Cascade Head Experimental Forest, Oreg., 1964-67*
(In pounds per acre)

Forest type	Sample year	SEASON				Yearly total
		Spring	Summer	Autumn	Winter	
Mixed	1	678	1,097	2,307	3,031	7,113
	2	819	1,237	2,166	1,059	5,281
	3	857	695	3,202	642	5,396
	Average	785	1,010	2,558	1,577	5,930
Alder	1	443	917	2,072	1,270	4,702
	2	549	1,196	1,908	765	4,418
	3	449	527	2,885	492	4,353
	Average	480	880	2,288	842	4,490
Conifer	1	846	550	1,511	1,889	4,796
	2	979	728	1,639	944	4,290
	3	646	314	1,955	691	3,606
	Average	824	531	1,702	1,175	4,232

A review of 163 published reports (Bray and Gorham 1964) indicates for a wide range of tree species that litter production in "cool temperate forests" of the world ranges from 2,204 to 6,157 pounds per acre per year and averages about 3,000. A few estimates of litterfall weight have also been reported for the tree species we studied. Dimock (1958) found, for a site of comparatively low productivity, that Douglas-fir litterfall weight averaged 1,575 pounds per acre per year over 6 years. On a site near that studied by Dimock and of similar productivity, Rahman[3] measured litterfall weights (pounds per acre per year) of 1,475 for Douglas-fir and 1,562 for red alder. Owen (1954) reported annual litterfall of 1,822 pounds per acre per year beneath a 20-year-old Sitka spruce plantation in North Wales. Thus, it appears that the stands at Cascade Head Experimental Forest are in the upper range of litter production for forests of the temperate zone.

In each of the three forest types, average litterfall weight varied with season. This highly significant (99-percent level of probability) variation is attributed to weather differences between years. Differences in total yearly litterfall were highly significant for the conifer stand but not for the mixed or alder types. Deciduous alder loses all its foliage yearly, which makes for uniformity in weight of leaf fall over several consecutive years in these comparatively mature stands. In contrast, conifer needles are released as litterfall only slowly unless sharp temperature and moisture variations occur. Dimock (1958) found that extremely low temperatures greatly increased Douglas-fir litterfall; but over 4 years in which such extremes did not occur, the magnitude of difference between the lowest and highest yearly litterfall weight was only about 1.4 times — about the same difference we found.

[3] Rahman, A. H. A study of the movement of elements from tree crowns by natural litterfall, stem flow and leaf wash. (Unpublished M.F. thesis on file at Univ. Wash.) 1964.

There was also a highly significant season-year interaction for each of the three forest types. In other words, the seasonal effect varied from year to year. We attribute this season-year interaction to variations in weather patterns and timing of phenological events which, of course, differ from year to year.

Nitrogen Concentration and Accretion in Litterfall

In each of the three forest types, N concentration (percent of dry weight) varied with season and year (table 2) and the season-year interaction was also highly significant. Differences between seasons within a single year are to be expected in view of the cyclic migration of nutrients within the tree. Differences between

TABLE 2.—*Total N in litterfall by forest type, year, and season of sampling; Cascade Head Experimental Forest, Oreg., 1964-67*
(In percent of dry weight)

Forest type	Sample year	SEASON				Yearly average
		Spring	Summer	Autumn	Winter	
Alder	1	2.49	2.63	2.82	1.43	2.34
	2	2.58	2.25	2.32	1.44	2.15
	3	2.44	2.12	2.36	1.18	2.03
	Average	2.50	2.33	2.50	1.35	2.17
Mixed	1	2.00	2.36	2.47	.94	1.94
	2	1.88	2.03	1.98	1.23	1.78
	3	1.81	1.88	2.04	1.21	1.74
	Average	1.89	2.09	2.16	1.13	1.82
Conifer	1	.91	.85	.90	.66	.83
	2	.81	.68	.74	.78	.75
	3	.90	.68	.76	.81	.79
	Average	.87	.74	.80	.75	.79

STUDY METHODS

The study was conducted at the Station's Cascade Head Experimental Forest on the Oregon coast at latitude 45°3′ N., longitude 123°55′ W. Here, experimental plots were established during 1935-37 to compare growth of pure red alder, pure conifer, and a natural mixed stand of red alder and conifers. The area occupied by the plots was formerly agricultural land which was abandoned about 1925.

Trees on the plots are now about 40 years old and occupy the following basal area (square feet per acre): alders, 156; conifers, 268; and mixed stand, 221. Soils beneath all three stands are Sols Bruns Acides, developed on a deeply weathered, tuffaceous siltstone of Eocene epoch. Detailed morphological and chemical characteristics of the soils are described by Franklin et al. (1968).

In June 1964, 15 ¼-milacre litter traps were placed in each stand. Traps were located in five groups of three each around randomly selected, previously numbered trees on each plot. Distance and direction of the traps from the trees were also determined by random selection.

Litterfall, defined as all plant material falling on the sampling areas, was collected from the traps at 3-month intervals—June-August, September-November, December-February, and March-May. These collection periods are hereinafter referred to, respectively, as "summer," "autumn," "winter," and "spring."

Immediately after the litterfall was collected, it was ovendried to constant weight at 70°C. and weighed to the nearest 0.1 gram. Samples were then analyzed for total N by the Kjeldahl method (Association of Official Agricultural Chemists 1960), and for carbon by use of a medium temperature resistance furnace after the method of Allison et al. (1964).

RESULTS

Litterfall Weight

The mixed stand contained 860 trees per acre, appreciably more than either conifer (490 per acre) or alder (381 per acre) stands. The mixed stand also generated the greatest weight of litterfall per year (5,930 pounds per acre per year) (table 1). Conifer and alder stands produced almost equal amounts of litterfall (4,232 and 4,490 pounds per acre per year) which was only about three-fourths that in the mixed stand.

TABLE 1.—*Litterfall weight by forest type, year, and season of sampling, Cascade Head Experimental Forest, Oreg., 1964-67*
(In pounds per acre)

Forest type	Sample year	SEASON				Yearly total
		Spring	Summer	Autumn	Winter	
Mixed	1	678	1,097	2,307	3,031	7,113
	2	819	1,237	2,166	1,059	5,281
	3	857	695	3,202	642	5,396
	Average	785	1,010	2,558	1,577	5,930
Alder	1	443	917	2,072	1,270	4,702
	2	549	1,196	1,908	765	4,418
	3	449	527	2,885	492	4,353
	Average	480	880	2,288	842	4,490
Conifer	1	846	550	1,511	1,889	4,796
	2	979	728	1,639	944	4,290
	3	646	314	1,955	691	3,606
	Average	824	531	1,702	1,175	4,232

A review of 163 published reports (Bray and Gorham 1964) indicates for a wide range of tree species that litter production in "cool temperate forests" of the world ranges from 2,204 to 6,157 pounds per acre per year and averages about 3,000. A few estimates of litterfall weight have also been reported for the tree species we studied. Dimock (1958) found, for a site of comparatively low productivity, that Douglas-fir litterfall weight averaged 1,575 pounds per acre per year over 6 years. On a site near that studied by Dimock and of similar productivity, Rahman[3] measured litterfall weights (pounds per acre per year) of 1,475 for Douglas-fir and 1,562 for red alder. Owen (1954) reported annual litterfall of 1,822 pounds per acre per year beneath a 20-year-old Sitka spruce plantation in North Wales. Thus, it appears that the stands at Cascade Head Experimental Forest are in the upper range of litter production for forests of the temperate zone.

In each of the three forest types, average litterfall weight varied with season. This highly significant (99-percent level of probability) variation is attributed to weather differences between years. Differences in total yearly litterfall were highly significant for the conifer stand but not for the mixed or alder types. Deciduous alder loses all its foliage yearly, which makes for uniformity in weight of leaf fall over several consecutive years in these comparatively mature stands. In contrast, conifer needles are released as litterfall only slowly unless sharp temperature and moisture variations occur. Dimock (1958) found that extremely low temperatures greatly increased Douglas-fir litterfall; but over 4 years in which such extremes did not occur, the magnitude of difference between the lowest and highest yearly litterfall weight was only about 1.4 times — about the same difference we found.

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years and between seasons between years can be attributed generally to slight shifts in time of phenological events from year to year and, probably more important, to differences in the physical composition of litterfall due to air temperature and wind intensity.

Over 3 years, average N concentration of alder litter was almost three times — and that of the mixed stand more than two times — that of conifer litterfall. During spring, summer, and autumn, N concentration in alder litterfall was more than three times that beneath the conifer stand, and mixed litterfall was nearly the same. In winter samples, the same qualitative relationships prevailed, but N concentration in both the alder-influenced stands was sharply reduced over that of the other three seasons. Absence of alder leaves and a preponderance of woody materials in winter litterfall undoubtedly influenced N concentration in winter samples. Although N concentration in alder leaves usually exceeds 2 percent, that of alder wood is only about 0.37 percent (Bollen 1953).

Weight of litterfall N (table 3) exhibited the same highly significant variations as were found for N concentration. Average yearly weight of N was almost the same for mixed and pure alder stands, 104 and 100 pounds per acre, but that of the conifer stand was only 32 pounds per acre.

A substantial portion of the N in alder and mixed-stand litterfall must be regarded as an accretion to nutrient capital. Yearly N accumulations in soil influenced by species of *Alnus* other than red alder range from 21 to 54 pounds per acre (Tarrant 1964), and an average over 30 years of 36 pounds per acre per year was reported for a plantation of red alder and Douglas-fir by Tarrant and Miller (1963). Over 268 pounds per acre of N may be added each year to an ecosystem dominated by red alder between tree ages 2 and 14 years, according to Newton et al. (1968). These authors also indicate that about 89 pounds per acre of N is brought down annually in red alder litterfall, an estimate substantiated by our study.

TABLE 3—*Total N in litterfall by forest type, year, and season of sampling; Cascade Head Experimental Forest, Oreg., 1964-67.*
(In pounds per acre)

Forest type	Sample year	SEASON				Yearly total
		Spring	Summer	Autumn	Winter	
Mixed	1	13.1	25.6	56.5	24.2	119.4
	2	14.9	24.9	42.6	13.3	95.7
	3	13.6	13.0	63.5	6.9	97.0
	Average	13.9	21.2	54.2	14.8	104.0
Alder	1	10.7	24.1	58.4	19.0	112.2
	2	13.9	26.9	44.2	10.6	95.6
	3	9.7	11.2	67.9	4.4	93.2
	Average	11.4	20.7	56.8	11.3	100.3
Conifer	1	7.9	4.6	14.0	11.3	37.8
	2	7.8	4.8	12.0	7.4	32.0
	3	4.9	2.1	14.3	5.4	26.7
	Average	6.9	3.8	13.4	8.0	32.2

We deducted the N content of conifer litterfall from that for both the alder and mixed stands to obtain a conservative estimate of the N that might be regarded as an addition to nutrient capital through symbiotic fixation of atmospheric N by red alder. On this basis, mixed-stand litterfall apparently provided an average annual N accretion to the study site of about 72 pounds per acre and alder litterfall provided about 69 pounds per acre. In the same stands, net annual N accretion in throughfall (leaf wash) and stemflow precipitation was, for mixed and pure alder stands respectively, about 1.8 and 2.4 pounds per acre (Tarrant et al. 1967). Thus, between the N accretion from litterfall and that of enriched throughfall precipitation, about 74 pounds per acre per year of N can be regarded as an addition to the mixed-stand ecosystem and about 70 pounds per year to that of the alder ecosystem.

Carbon-Nitrogen Ratio

Over all years and seasons, the C:N ratio of conifer litter averaged 69 (table 4), but that of alder (27) and the mixed stand (32) were both less than half that value. There was little difference between the C:N ratio of litterfall collected in spring, summer, or autumn seasons beneath either alder or the mixed stand, but the C:N ratio was always greatest in winter-collected samples. This difference is attributed to low-nitrogen limbwood in alder-influenced stands, which falls in especially great amounts during winter storms.

TABLE 4.—*Carbon:nitrogen ratio in litterfall by forest type, year, and season of sampling; Cascade Head Experimental Forest, Oreg., 1964-67.*

Forest type	Sample year	SEASON				Yearly average
		Spring	Summer	Autumn	Winter	
Conifer	1	57	64	60	85	67
	2	62	79	71	69	70
	3	60	80	72	69	70
	Average	60	74	68	74	69
Mixed	1	26	23	21	59	32
	2	30	26	27	44	32
	3	30	28	27	46	33
	Average	29	26	25	50	32
Alder	1	21	20	19	49	27
	2	21	23	22	37	26
	3	23	25	23	44	29
	Average	22	23	21	43	27

DISCUSSION

Soil N at the site we studied is probably near the limit of accumulation for forest soils of the Pacific Northwest. Beneath the conifer stand, soil N to a depth of 36 inches totaled 11,720 pounds per acre (Franklin et al. 1968). Beneath the mixed stand, the comparable value for soil N was 12,640 pounds per acre and beneath pure alder, it was 16,680 pounds per acre. These values, the highest yet reported for Pacific Northwest forest soils, are near the maxima found in the highly productive redwood (*Sequoia sempervirens* (D. Don) Endl.) region of northern California (Cooper 1965).

A number of investigators, including Zavitkovski and Newton (1968), have shown that N-fixation by alder seedlings is reduced in the presence of high levels of combined N. Although our data for large trees neither support nor deny this finding, it is evident that even under conditions of very high total soil N, alder fixed large quantities of N. All trees on the study site began as natural regeneration on a forest clearing which had been in pasture for a number of years. After about 40 years of tree growth, soil beneath alder had 4,960 pounds per acre more N than that under conifers — indication of an average annual accretion to soil N of about 124 pounds per acre.

Although this early-established study area included only one plot for each forest type and thus allowed no possibility for statistical comparisons between stands, our observations agree very closely with those of Newton et al. (1968), who estimated that as much as 4,460 pounds per acre of litter is deposited annually beneath alder and that about 89 pounds per acre of N is added to the soil in this litterfall. The difference between the average N accretion of 124 pounds per acre per year in soil beneath pure alder over 40 years and the current accretion of 70 pounds per acre from alder litterfall and enriched precipitation suggests that the rate of N-fixation in stands we studied must at one time have been substantially greater than it is now.

Newton et al. (1968) measured annual N-fixation rates of as much as 286 pounds per acre in dense stands of red alder ranging from 2 to 14 years old, and concluded that equilibration of the N-fixation rate in soil tended to occur before tree age 20 years. Rates of N-fixation were substantiated by greenhouse studies (Zavitkovski and Newton 1968) which indicated that annual N-fixation by red alder could approach 89 pounds per acre during the first year of growth and reach as much as 186 pounds per acre per year in 30-year-old stands. These rates of fixation, the highest yet reported for red alder, appear to be entirely possible in light of our findings, which do not include N content of the biomass exclusive of soil.

Current accretion to soil N in litterfall and enriched precipitation was virtually the same for alder and mixed stands, yet average soil N accumulation over the life of the mixed stand was only 23 pounds per acre per year — about one-fifth of that in the pure alder. We believe the explanation for this difference lies not in any substantial difference in N-fixing rates between the two forest types but rather in the nature of the stands. A minor but contributing factor influencing soil N beneath the mixed stand and pure alder is the difference in number of alder trees. The pure alder stand had 381 trees per acre with a total basal area of 157 square feet per acre, whereas the alder component of the mixed stand amounted to 363 trees per acre with 135 square feet per acre total basal area. Probably of greater significance is the fact that the mixed stand had a total (alder plus conifer) of 860 trees per acre more than twice the number in the alder stand — and a total stand basal area of 222 square feet per acre. Thus, the mixed stand offers much greater opportunity for nitrogen storage in the vegetative mass than the pure alder stand, especially the conifer component which does not shed foliage annually.

For at least the first 40 years of its growth, red alder, in its litterfall, annually contributes the equivalent of a heavy N fertilizer application over and above the amount normally cycled in a conifer forest on the same site. This added N is rapidly made available for tree nutrition and increases growth of associated conifers (Tarrant 1961). Other benefits noted from the influence of red alder on the ecosystem include increased soil organic-matter content and porosity (Tarrant 1961) and, possibly, reduction of the incidence of soil-borne pathogens that cause forest losses from root diseases (Li et al. 1967).

Before red alder was shown to be a biologically valuable component of managed forests, foresters often regarded it only as an undesirable intruder onto sites believed more properly to be reserved for production of conifers. Red alder has strong pioneering ability on newly bared lands because of its ability to supply its own needs for nitrogen, which usually is the major limiting nutrient element for good tree growth in Pacific Northwest forests. Because of its rapid early growth, unmanaged red alder can dominate associated conifer seedlings during early years of stand development. Thus, when alder reproduces naturally on upland sites, it may impede establishment of other tree species and thus hinder full forest production.

Chemicals are widely used to kill red alder where it interferes with growth of conifers, but cautions have been sounded as to the need for reappraising present concepts of large-scale brush eradication. Tarrant (1964) pointed out that even with substantial evidence of the soil-improving quality of many species of *Alnus*, study of its application to silvicultural practice has not kept pace with other forestry research. Youngberg (1966) observed that in most situations where brush and weed plants are removed to enhance growth of economically more valuable tree species, little or no thought is given to the loss of beneficial effects exerted by many of the plant species being eradicated. And, Egler (1964) was even more emphatic in his views: "foresters can be remarkably ignorant . . . of long-term reactions from the loss of nitrogen-fixing 'pest plants' such as alder."

We see no real conflict in divergent viewpoints on the value of red alder in Pacific Northwest forest management but consider the matter

rather as one in which understanding of the value of alder as a potentially useful adjunct to managed forest stands is not yet widespread. Like most other trees, alder can become a weed requiring control or it can be managed to produce a silvicultural and economic benefit. In view of the rapid conversion of wild forests to intensively managed systems in Pacific Northwestern United States, we suggest that the demonstrated ability of red alder to enhance forest soil fertility and forest productivity is a biological tool that we must learn to use effectively.

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Nitrogen content and total weight of litterfall were determined seasonally over 3 years in 40-year-old coastal Oregon forests of pure conifer (Douglas-fir, western hemlock, Sitka spruce), pure alder, and a mixture of the conifers and alder. Either in pure stand or as an admixture with conifers, red alder led to about a threefold increase in the amount of nitrogen circulating in litterfall.

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Headquarters for the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is in Portland, Oregon. The Station's mission is to provide the scientific knowledge, technology, and alternatives for management, use, and protection of forest, range, and related environments for present and future generations. The area of research encompasses Alaska, Washington, and Oregon, with some projects including California, Hawaii, the Western States, or the Nation. Project headquarters are at:

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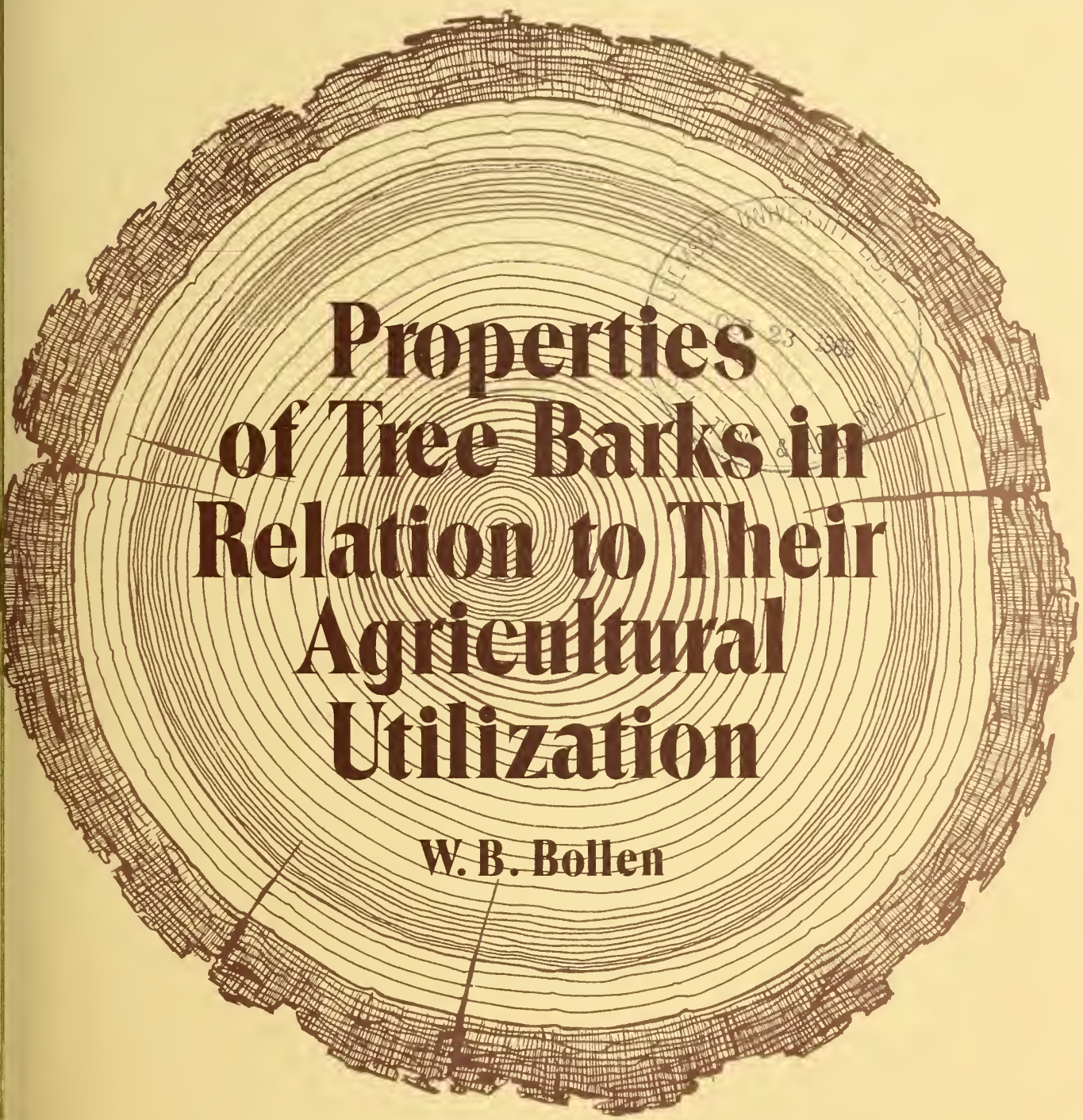

Properties of Tree Barks in Relation to Their Agricultural Utilization

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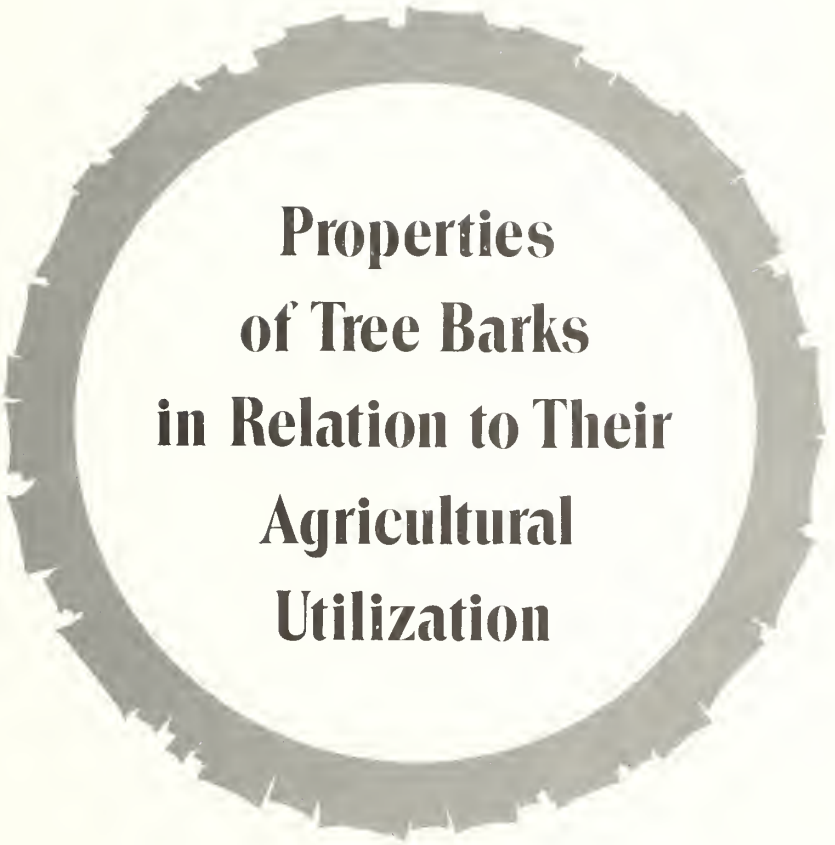

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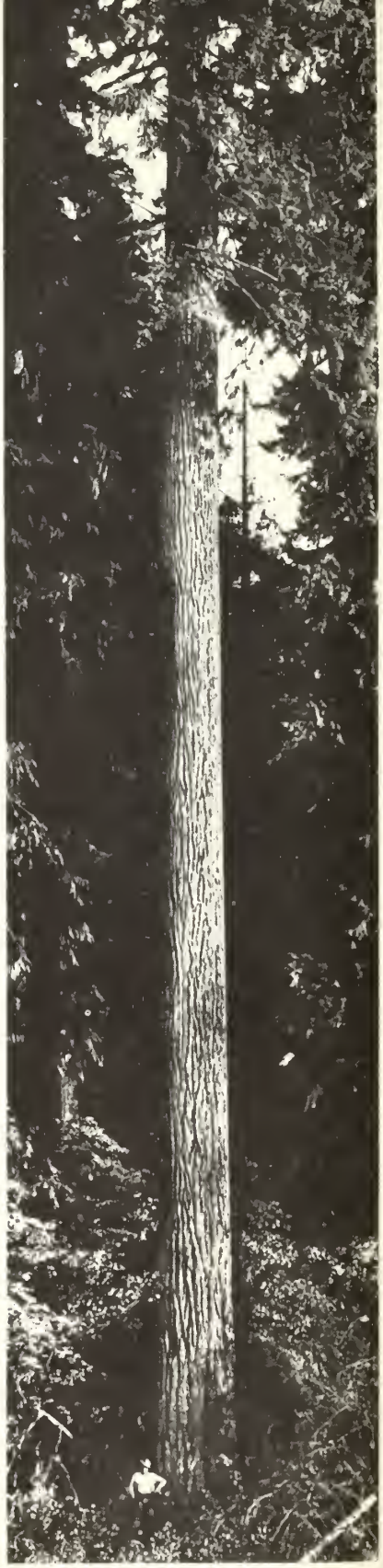

A mature, old-growth Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, the species from which most of the bark in the Pacific Northwest is derived.

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Introduction

About 5 million tons of tree bark were produced in 1966 as "waste" from the Pacific Northwest wood products industry, more than two-thirds of which (table 1) came from Oregon and Washington.[1] If all this bark were to be concentrated in one place, the resulting pile would cover 1 square mile to a depth of 10 feet.

Other regions also produce large amounts of bark. The British Columbia lumber industry in 1963 produced 116 million cubic feet or about 1.5 million tons of bark, of which 48 percent was Douglas-fir, 22 percent was western hemlock, and the remaining 30 percent was from all other commercial tree species.[2]

Bark of major tree species of the Pacific Northwest constitutes a sizable portion of the log:

Tree species	Percent of gross log volume in bark
Douglas-fir (*Pseudotsuga menziesii*)	
Old growth	12-15
Young growth	8
Redwood (*Sequoia sempervirens*)	20
Ponderosa pine (*Pinus ponderosa*)	12
True firs (*Abies* spp.)	11
Western redcedar (*Thuja plicata*)	10
Western hemlock (*Tsuga heterophylla*)	8
Spruce (*Picea* spp.)	7

Tree bark has relatively little economic use at present, so disposal of this material poses a major industrial problem. In some cases, bark is buried in trenches or landfills. However, most mills dispose of their bark by burning, either for fuel or in wigwam burners. The smoke and particulate fallout thus created is a significant source of air pollution and a critical problem in areas of mill concentrations.

Federal laws require all States to enact pollution control measures. The Oregon Sanitary Authority has developed standards for water and air quality control which are being enforced within the limits of present day technology. The State of Washington is also developing such standards.

We urgently need to develop economic uses for bark to help solve a critical problem in the Pacific Northwest (Mater 1967).[3] This need will become greater, not only because of current and pending air pollution regulations but also because of high stumpage prices calling for maximum utilization of every part of the log (Cruickshank 1968).

In some localities, as much as 10 percent of the bark available is used in agriculture. A conservative estimate of bark so utilized in the Pacific States is about 100,000 tons per year.[4]

The amount of moss peat[5] marketed annually in the United States is approximately

[1] *Estimates of bark production were made from 1966 production of lumber and plywood. The Pacific Northwest, for purposes of this paper, includes Oregon, Washington, Idaho, western Montana, and northern California.*

[2] *Personal communication from Mr. E. Kerbes, Forest Products Laboratory, Vancouver, B.C. 1968.*

[3] *Names and dates in parentheses refer to Literature Cited, p. 32.*

[4] *From replies to a questionnaire sent in 1968 to county extension agents and sawmills.*

[5] *Moss peat, often incorrectly called "peat moss," is derived from mosses, usually species of* Sphagnum *or* Hypnum, *which undergo only partial decomposition in bogs and marshes because of lack of dissolved oxygen (Dachnowski-Stokes 1931). The arrested decomposition of this submerged organic material results in the formation and accumulation of "peat." Dried and shredded peat is marketed as "peat moss," although actually it is a peat derived from moss (Dachnowski-Stokes 1931, Schreiner and Shorey 1909). Dried, undecomposed sphagnum moss is also available as a medium for plant propagation by seed or cuttings. It is sterile and is prized for its property of inhibiting damping-off fungi (Crecch et al. 1955).*

Table 1. — Estimated annual production of bark in Oregon and Washington, by species and log volume, 1966[1]

Species	Log volume	Bark per M bd. ft., log scale	Total bark	
	Billion bd. ft.	Cubic feet	Million cu. ft.	Tons[2]
Douglas-fir	8.20	20.0	164	2,510,000
Hemlock	1.84	12.5	23	328,000
Ponderosa pine	1.65	18.0	30	290,000
True firs	1.20	17.0	20	220,000
Redcedar	.40	15.0	6	69,000
Spruce	.18	11.0	2	20,000
Total			245	3,437,000

[1] *Estimate by Pacific Northwest Forest & Range Experiment Station, Portland.*

[2] *75 percent water content, ovendry basis.*

500,000 tons (Sheridan and De Carlo 1957). Bark could replace much of this material.

The possibilities for using large quantities of bark in agriculture are greater than might first be imagined. One encouraging development is use of waste bark as a replacement for the great amounts of sawdust and other fine wood wastes used in the past for mulches, soil conditioners, animal bedding, etc.

Sawdust, wood shavings, and chips are now in strong demand for pulping purposes in the Pacific Northwest. Some of the material is shipped to Japan, but most is consumed in the domestic market. County extension agents point to the growing scarcity of sawdust and shavings for farm use and call for more research on bark as a replacement material.[6] Another indication of the increasing demand for agricultural grades of bark is the growing number of mills and dealers now advertising such products for sale. Some representative prices for unamended bark are:

Portland, Oregon: Douglas-fir and hemlock bark, $15 per unit (200 cubic feet) delivered within city limits;

Medford, Oregon: Douglas-fir and white fir, $5 per unit, wholesale at the mill;

Corvallis, Oregon: Hemlock bark, $1 per 2-cubic-foot bag; Douglas-fir bark, $0.80 to $1 per 2½-cubic-foot bag; spruce bark, $3.50 per cubic yard in bulk at a local nursery; hemlock and Douglas-fir bark mixed, in bulk, $15 per unit delivered; and

California: Amended pine and white fir bark, $3 per 3-cubic-foot bag; in bulk, $7 to $14 per cubic yard, according to delivery distance.

The time is ripe to solve the troublesome problem of waste bark disposal with its attendant contribution to air pollution. In this paper, we shall discuss the possibilities for use of large volumes of bark for agricultural purposes and summarize our knowledge of the various properties of bark having a direct bearing on its use.

[6] *See footnote 4.*

Preparing bark for agricultural use

Bark is mechanically removed from logs by variously designed cutter heads, scrapers, or hydraulic debarkers which direct high pressure jets of water against the log. After this process, bark is ground in a hog mill or hammer mill, then screen-sorted into size ranges appropriate for the intended use. Water content of bark varies with the debarking method used and whether the log had previously been stored in water. Some drying, accomplished by allowing the bark to heat spontaneously in deep piles, may be necessary to obtain satisfactory grinding and screening. On the other hand, wet grinding would reduce dust and give a more fibrous product. Slotted screens effectively remove many wood slivers which detract from appearance of the bark.

Further processing — composting, ammoniation, pelletizing, or adding fertilizers and pesticides — may follow to enhance the value of bark. Stabilization, or satisfying the nitrogen demand of the microbial population, is often included as an additional feature. Rarely, however, are barks sufficiently fortified with plant nutrients to be considered fertilizers.

Ash (mineral) content is generally greatest in tree leaves or needles followed in order by that in bark, branches, and wood (Anonymous [n. d.], Lutz and Chandler 1946) (table 2). Bark has almost no plant nutrient value (tables 2 and 3), although in most cases bark nutrient content is higher than that of sawdust. Nitrogen content is very low. Ash is also

Table 2. — Some chemical characteristics of Douglas-fir bark, wood, and needles compared with alfalfa hay and wheat straw

(In percent, ovendry basis)

Chemical characteristic	Bark	Sapwood	Heartwood	Needles	Alfalfa hay	Wheat straw
Total carbon	53.97	49.36	51.51	55.75	43.15	44.70
Kjeldahl N	.11	.09	.12	.96	2.34	.12
C/N ratio[1]	491:1	548:1	429:1	58:1	18:1	373:1
Hot-water extractives	2.50	2.70	4.20	12.10	16.90	5.00
Cold-water extractives:						
Total	1.90	1.00	4.80	22.00	23.10	7.80
Reducing sugars	.79	.14	.77	5.65	2.70	3.98
Kjeldahl N	.04	.09	.13	.16	1.13	.48
C/N ratio[2]	1,250:1	556:1	385:1	313:1	44:1	104:1
Ash	.50	.30	.30	5.60	8.80	8.50
Alcohol extractives	13.70	3.50	8.10	36.60	15.70	8.00
Alcohol-benzene extractives	.20	.10	.30	.30	.60	.40
Holo-cellulose	42.20[3]	52.20	60.60	20.50	29.80	62.90
Klason lignin	41.60[3]	37.40	25.90	20.30	14.30	13.50
Crude protein	.70	.60	.80	6.00	14.60	.80

[1] *Not expressed as percent.*

[2] *Approximate: based on C = 50 percent.*

[3] *Not typical wood cellulose or lignin.*

Table 3. — Major plant nutrients in bark, sawdust, and moss peat

(In percent, dry basis)

Material	N	P	K	Ca	Mg
Bark:					
Douglas-fir	0.12	0.011	0.11	0.52	0.01
Ponderosa pine	.12	.003	.11	.25	.01
Redwood	.11	.011	.06	.29	.00
Red alder[1]	.73	.153	.24	1.25	.18
Sawdust:					
Douglas-fir	.04	.006	.09	.12	.01
Ponderosa pine	.04	.008	.12	.16	.02
Redwood	.07	.001	.01	.20	.02
Red alder	.37	.013	.12	.18	.04
Moss peat	.83	.030	.02	.50	.12

[1] Alnus rubra *Bong.*

low, but calcium is relatively high compared with other minerals. Phosphorus concentration is much less than that of nitrogen but is higher in bark of Douglas-fir and redwood than that of other tree species.

Nutrient content of bark differs not only with species but also with age of tree, environmental factors, and growing site. Bark content, especially of minor or "trace" elements, varies with the location in which the tree was grown (Ellis 1959, 1965). The amount of mineral elements in bark often reflects differences in availability of the element in soil rather than the amount necessary to satisfy nutritional needs of the tree.

In table 2, some chemical properties of Douglas-fir bark are compared with those of Douglas-fir wood and needles and with two agricultural residues commonly incorporated with soil — alfalfa hay and wheat straw. Douglas-fir bark contains more ash, alcohol extractives, and lignins than wood of the same species. Douglas-fir needles are notably higher than the wood in ash, sugars, and nitrogen. Alfalfa hay and wheat straw are also higher in the properties measured than is Douglas-fir bark or wood and thus more susceptible to rapid decomposition. Cold-water extractives are much higher in needles, alfalfa hay, and wheat straw than in bark or wood. These extractives represent water soluble constituents that would exert most of the immediate demand for nitrogen after being leached from bark into the soil by rain or irrigation. Before reaching the soil, some of these water soluble materials would probably undergo some decomposition in the bark itself by indigenous microbes and thus would not use nitrogen in the soil.

Ammoniation

Ammoniation, a relatively new process, is one way in which bark can be fortified with nitrogen which, as we shall see, is vital to the successful use of bark on or in the soil. Due to the presence of polyphenols, bark is highly acid and readily absorbs ammonia when wet. Spraying ground bark with aqua ammonia can add about 2 percent nitrogen (Bollen and Glennie 1963), more than is required for the complete microbial decomposition of bark over 6 to 10 years. Nitrogen, assimilated by microbes in early stages of organic matter decomposition, is released upon their death and becomes available for subsequent organisms attacking the more resistant residues.

Exposing Douglas-fir bark to anhydrous ammonia in a closed screw conveyor system

readily added 4 percent nitrogen in experiments conducted by Aspitarte[7] and Bollen and Glennie (1963). In a much simpler process, anhydrous ammonia gas is admitted through perforated pipes at the bottom of a 5-foot-deep bark pile covered with polyethylene sheets (fig. 1). Ammoniated bark is much darker than raw bark (fig. 1).

Bark must be wet for ammoniation to be effective. Portions of the pile near the points of gas admission become darker and more highly ammoniated. For a uniform product, the pile must be turned and allowed to cure after treatment, permitting equal distribution of the added nitrogen and escape of any free ammonia which might otherwise volatilize from the product when used as a mulch. An excess of ammonia could also cause too high a pH in the mulch or soil which could injure some plants.

A total nitrogen content of about 2 percent is obtained by ammoniation. Bark so treated, sometimes called stabilized or composted bark, has a pleasing dark color. Bollerslev (1968) describes a successful commercial operation wherein the best product is produced by composting ammoniated bark at 135° to 150° F. for approximately 90 days.

Ammoniation also softens the needlelike bast fibers of Douglas-fir so that they lose much of their objectionable handling properties. Ammoniated or otherwise fortified bark products should be positively labeled; otherwise, users may add nitrogen fertilizer and cause undesirable growth effects on plants.

Cork and fine bark fractions absorb more ammonia with longer exposure, but they absorb it differentially. Ricard[8] found that Douglas-fir bark fibers treated with anhydrous ammonia at room temperature and atmospheric pressure had a nitrogen content of about 3 percent. For the cork fraction, the value was 5.5 percent and for fines, 7 percent.

Half of the nitrogen introduced into Douglas-fir bark by ammoniation is not readily available to plants or to ammonifying organisms and is only slowly nitrified (Bollen and Glennie 1963). This slowly available portion of the nitrogen provides a reserve for subsequent demands by succeeding crops and against nitrification and possible loss of nitrate by leaching. Much of the nitrogen introduced by treatment with nitric acid or urea likewise is only slowly available. Bremner and Shaw (1957) found that nitrogen in nitrated pine sawdust was mineralized much more slowly than nitrogen in nitrated lignin. Lignin ammonia reaction products also decomposed less rapidly than nitrated lignin. More of the total nitrogen in nitrated sawdust is attached to the cellulose than to the lignin. Similar results would probably be found with bark whose major components are cellulose and lignin (table 2).

Composting[9]

Composting speeds the recycling of nutrients and stabilizes bark while overcoming its nitrogen deficiency. In the composting

[7] *Aspitarte, T. R. Availability of nitrogen in ammoniated bark used as a soil amendment. 1959. (Unpublished Ph.D. thesis on file at Oregon State Univ., Corvallis.)*

[8] *Personal communication from Dr. J. L. Ricard, Forest Research Laboratory, Oregon State University. 1968.*

[9] *A bibliography with abstracts on "Sawdust and Bark for Composting and Mulching," covering the literature for 1949-67, is available from the Commonwealth Bureau of Soils, Harpenden, England. Of 78 publications reviewed, 14 deal with bark. A more recent, larger "Bibliography of Wood Waste Composts," by Seiji Uemura is available (in English) from the Ministry of Agriculture and Forestry, Government Forest Experiment Station, Meguro, Tokyo, Japan. These references and further Japanese research are discussed in detail (in Japanese) in an accompanying 271-page booklet, "Ringyo-Kairyo-Fukyu-Sosho" (translated title "Wood Waste Compost Manufacture and Applications").*

Figure 1. — Ammoniated bark darkened in comparison with untreated bark.

Figure 2. — Fermented center of large sawdust pile.

process, organic residues undergo sufficient decomposition to narrow the C:N ratio, much of the carbon passing off as carbon dioxide. The action should be allowed to proceed to near humification where some nitrogen becomes available as ammonium or nitrate. Materials of wide C:N ratio require addition of nitrogen fertilizers or readily decomposable nitrogenous wastes. Calcium cyanamid is a useful adjunct because, in addition to supplying nitrogen, it neutralizes acidity arising from fermentation and promotes microbial activity.

Combining fresh vegetable refuse with bark not only supplies additional nitrogen to the material but increases the composting action by hastening development of an active microbial population. Manure or sewage sludge may also be used in combination with bark. Watering and turning the pile controls the moisture, aeration, and temperature. Gessel (1959) and Macdonald and Dunn (1953) found that composted bark was superior to composted sawdust in promoting growth of cabbage in pot tests. Wood residues composted with poultry manure and rice bran have been found to depress many plant pests, apparently because the compost contains an abundance of antibiotic-producing microbes such as *Trichoderma* and *Streptomyces.*[10]

Composted wood residues provide intangible growth-promoting substances as well as available plant nutrients so they command premium prices. The darker color imparted by composting, especially of sawdust which is much lighter colored than bark, is an attractive feature.[11] Composts also have the capacity to counteract toxicities of biocides (Mader 1960).

Composted bark can be produced at a profit where raw materials and facilities for their processing are available. Some lumber mills in California have composted bark on a large scale. Ivory and Field (1959) point to a big market for composted bark; they also emphasize that the inherent qualities of bark produce a good compost and that special bacteria need not be introduced. Dost (1965) has mentioned composting of bark from pine and true fir species. A few Oregon mills and fuel dealers also market raw and composted bark (fig. 3). Such processing, however, is not likely to be undertaken by a mill which produces large quantities of bark that could be supplied to another enterprise willing to undertake the risks involved.

[10] *Personal communication from Dr. Seiji Uemura, Government Forest Experiment Station, Meguro, Tokyo, Japan. 1968.*

[11] Warning: *Raw sawdust that has darkened due to spontaneous heating by fermentation and subsequent chemical action in large compacted piles (fig. 2) is strongly acid and should not be applied to the soil (Bollen and Lu 1966). As much as 300 pounds of limestone may be required to neutralize 1 ton of such sour sawdust, dry basis. The acid, mainly acetic, imparts a pungent and irritating odor, which should warn against its use. Raw bark is susceptible to a similar fermentation.*

Figure 3. — Loamite and different brands of bark marketed in Oregon.

Decomposition and fate of bark in soil

Bark is a complex physical and chemical mixture of many organic compounds, mainly lignocelluloses and extractives, as shown in the following tabulation:

Structural components:

- Carbohydrates
  - Holocelluloses
  - Hemicelluloses
  - Galactans
  - Mannans
  - Glucosans
  - Arabans
  - Uronic acids
- Lignin
- Cork
  - Suberic acid
  - Suberin
  - Cutose
  - Quercitin
  - Dihydroquercitin

Nonstructural components:

- Coloring matter
- Tannins and related condensed tannins
- Polysaccharides, glucosides, sugars, and gums
- Volatile acids and oils
- Nonvolatile fatty oils and steroids
  - Higher alcohols
  - Resins
  - Hydrocarbons
  - Polyphenols
- Miscellaneous organic materials
- Ash (minerals)

These compounds are attacked differentially by a wide variety of microbes during decomposition or mineralization. All the physical, chemical, and biological reactions and interreactions between bark and soil are controlled by factors of environment, including water, temperature, aeration, pH, nutrients, and biological influences. Optimum conditions for desirable microbial activities are:

1. Moisture near field capacity or 50 percent of the water-holding capacity;
2. Temperature near 80° F.;
3. Aeration that occurs when water supply is near optimum;
4. pH close to neutral;
5. Nutrient supply balanced;
6. A carbon:nitrogen ratio approximating 25:1 for readily decomposable substances;
7. An active microbial population, especially in the vicinity of the root rhizosphere (Bollen 1959).

Extreme environmental conditions are inhibiting or toxic to microbes, but ranges over which microbial activities take place are quite wide. Important physical, chemical, and biological properties of barks, which vary with species and origin and influence their effects on and in the soil, are listed below:

Physical:

- Color
- Particle size distribution
- Structure
- Specific gravity
- Bulk density
- Water-holding capacity

Chemical:

- Proximate analysis
  - Carbohydrates
  - Fats
  - Protein
  - Ash
- Ligno-celluloses
- Phenolics and other extractives
- Carbon/nitrogen ratio
- Mineral elements

Biological:

- Age of tree from which bark was derived
- Site on which tree was grown
- Cork and bast
- Contaminants

Size of particles and their distribution influence surface-to-volume ratios and interspatial properties.[1 2] These factors must be considered in interpreting physical, chemical, and biological effects of materials added to soil. Rate of decomposition of red alder and Douglas-fir wood particles, ranging from approximately 0.002 to 2 millimeters, was found to increase as surface exposure increased (Neal et al. 1965) (fig. 4). Douglas-fir decomposed slower than red alder.

Shape of particles is also important. Surface-to-volume ratios change more rapidly with spherical than with cylindrical shapes; materials that yield granular particles, such as red alder and spruce barks, will exhibit certain properties more than hemlock or cedar bark screened through the same mesh size because many of the particles of the latter are elongate. Although Allison (1965) found that -6 mesh pine wood decomposed about as rapidly as a finer grind, this may have been because ground pine and some other ground woods contain many slivers.

Differences in chemical composition of plant sample fractions resulting from grinding and screening may also affect rates of decomposition. Smith et al. (1968) found the percentage composition of N, P, Ca, Mg, and SiO_2 in wheat straw, barley straw, alfalfa, and corn leaves generally increased as particle size decreased from 20 mesh to 100 mesh.

Water-soluble constituents of bark are most rapidly consumed by microbes, exert most of the nitrogen demand, and require none of the more specialized bacteria that consume cellulose and ligninlike material. Few kinds of microbes are now known to utilize lignin. These organisms include some higher fungi, *Fomes annosus* and other white rot basidiomycetes, and the *Streptomyces*, a group of moldlike higher bacteria. *Trichoderma lignorum* is one of the few species of common soil molds that attack lignin. Only recently have some true bacteria been shown to act on lignin and ligninlike substances; these include certain species of *Agrobacterium*, *Pseudomonas*, and *Mycobacterium* (Sundman 1961, 1964a, 1964b). However, a wider variety of microbes may be involved in lignin decomposition in the soil (Sundman et al. 1964). Although lignin is highly resistant, it is decomposed almost completely by the specialized microbes under aerobic conditions, the chief end products being carbon dioxide, water, and microbial cells. Bacteria, because of their great abundance in the soil and their most extensive surface area which reflects biochemical activity, could well play a significant role in degrading lignin to humus.

Much is unknown about the chemical and physical nature of native lignin, especially bark lignin. It is closely associated with cellulose, either as an encrustant or by chemical bonding (Pew 1967). In either case, lignification protects the cellulose against cellulolytic

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[1 2] *Mesh dimensions (square openings) of Tyler standard sieves:*

Mesh designation	Mm.	Mesh designation	Mm.	Mesh designation	Mm.
6	*3.36*	*60*	*0.250*	*200*	*0.074*
9	*2.00*	*100*	*.149*	*250*	*.063*
10	*1.68*	*170*	*.088*	*325*	*.044*
16	*1.000*			*400*	*.037*

Only spherical particles just passing through the screens would have the exact dimensions indicated. Irregular pieces could be smaller or larger in volume. Slivers especially, because of their tendency to "dive" through the openings, present more bulk and surface than do blunt particles of the same mesh size.

All material passing a given mesh is indicated by a minus (–) sign; material retained on the mesh is indicated by a plus (+) sign. Thus, -6 shows that all passed through; -10+40 indicates material passing through 10 mesh but retained on 40 mesh.

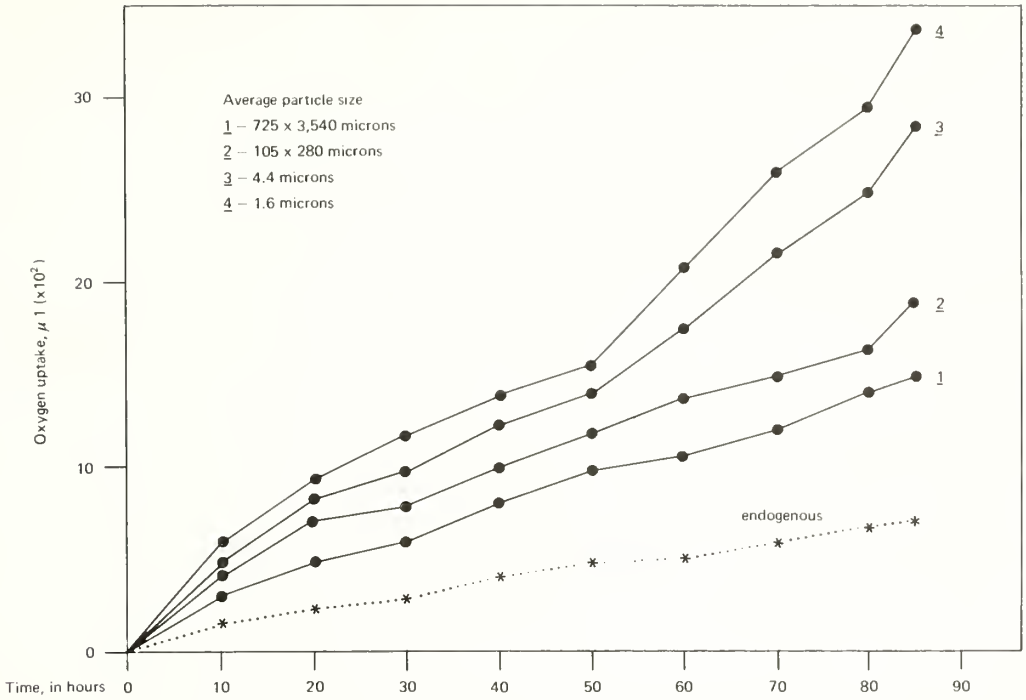

Figure 4. — Relation of particle size to rate of decomposition.

organisms and isolated enzymes. Certain microbes attack the lignin and thus expose the cellulose to attack by other organisms. Lignin metabolizers generally act slowly; this, with the cellulose-protecting role of lignin, accounts for the slow decomposition and low nitrogen demand for most bark and wood substance added to the soil.

Figures 5 and 6 show generalized courses of the reactions taking place when organic matter is decomposed or mineralized. Aerobic reactions, which take place in the presence of free oxygen, are more complete and more desirable in the soil than are anaerobic transformations. Anaerobic conditions in soil are induced by excessive water and also, at least

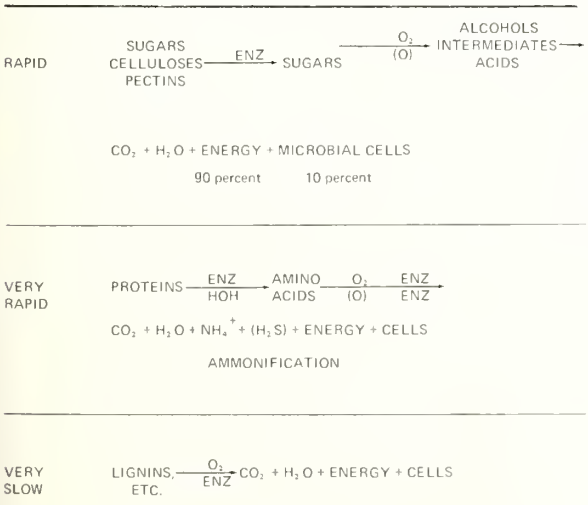

Figure 5. — Microbial decomposition of organic matter constituents.

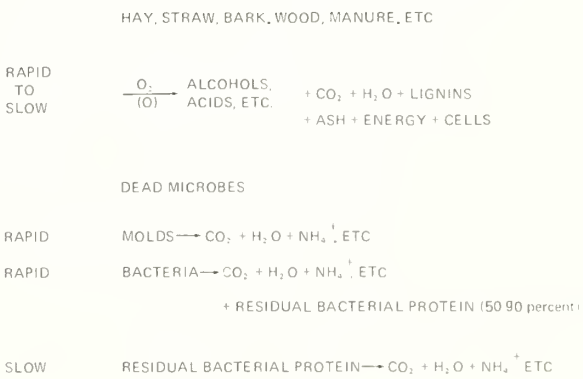
HAY, STRAW, BARK, WOOD, MANURE, ETC
RAPID TO SLOW
O₂ (O)
ALCOHOLS, ACIDS, ETC.
+ CO₂ + H₂O + LIGNINS
+ ASH + ENERGY + CELLS
DEAD MICROBES
RAPID
MOLDS → CO₂ + H₂O + NH₄⁺, ETC
RAPID
BACTERIA → CO₂ + H₂O + NH₄⁺, ETC
+ RESIDUAL BACTERIAL PROTEIN (50-90 percent)
SLOW
RESIDUAL BACTERIAL PROTEIN → CO₂ + H₂O + NH₄⁺ ETC

Figure 6. — Microbial decomposition of complex organic matter.

in microclimates within the soil, whenever a fresh addition of organic matter causes competition for free oxygen. Eventually, however, products of anaerobiosis will be oxidized whenever free oxygen becomes available.

Under favorable conditions, bark decomposes most rapidly during the first few days of exposure to microbial activity (Allison 1965, Bollen and Glennie 1961). Old-growth Douglas-fir bark decomposes more slowly than young-growth bark; ammoniated bark and moss peat are quite resistant to decomposition (table 4).

Laboratory studies by Allison (1965) on the decomposition in soil of -6 mesh woods and barks from 28 species of trees showed that during 60 days only two barks, those from incense-cedar (*Libocedrus decurrens*) and eastern redcedar (*Juniperus virginiana*) were oxidized more rapidly than the corresponding wood (table 5). Of 19 softwood species, the wood from shortleaf pine (*Pinus echinata*) decomposed most rapidly and that from eastern redcedar decomposed slowest; bark from lodgepole pine (*Pinus contorta*) decomposed most rapidly, redwood bark least rapidly. The mean value for the woods was 12.8 percent; for the barks, 8.8 percent. Over periods up to 800 days, however, decomposition of the woods ranged from 35 to 65 percent whereas for bark the range was 21 to 55 percent. Wheat straw decomposes much faster (Bollen and Glennie 1961).

The soil used in Allison's experiment supplied sufficient nitrogen for a maximum rate of decomposition of the barks and woods. Added sources of nitrogen in many cases decreased CO_2 evolution. Although this phenomenon is not uncommon when mineral nitrogen fertilizers are added with organic matter (Bollen and Glennie 1961, Bollen and Lu 1957), no adequate explanation has been

Table 4. — **Decomposition of bark, wood, and other organic materials in silt loam soil incubated at 28° C. and 50 percent of water-holding capacity**[1]

Material	Carbon released as CO_2 in 50 days	
	Bark	Wood
	Percent	
Douglas-fir:		
Young growth	26	30
Old growth	18	--
Ammoniated (2.83 percent N)[2]	5	--
Red alder	18	40
Western hemlock	16	27
Ponderosa pine	21	33
Western redcedar	8	33
Dextrose[3]	58	
Wheat straw[3]	48	
Moss peat	4	

[1] *-60 mesh materials incorporated with soil at 2,000 p.p.m. carbon. Data from Bollen and Glennie (1961) and Bollen and Lu (1957).*

[2] *T. R. Aspitarte (see text footnote 7).*

[3] *Standards for comparison.*

offered. Even with physiologically acid sources such as ammonium sulfate, the addition of some form of lime to ensure a favorable pH does not always increase the total CO_2 evolution. Possibly the added nitrogen relieves the soil microbes from obtaining their requirements by decomposing humus or other native organic nitrogen material, accordingly reducing the overall output of CO_2 .

Differences in rates of bark decomposition between data presented in tables 4 and 5 are attributed to differences in particle size of organic materials used in the two studies, soil types, and experimental techniques. However, results of our studies (Bollen and Glennie 1961) indicated generally that bark of commercially important western tree species decomposes more slowly than corresponding wood.

Figure 7 illustrates the importance of the carbon:nitrogen ratio, and why nutrient nitrogen must be added to highly carbonaceous materials so that microbes involved in the decomposition will not seriously compete with plant roots for their nitrogen requirements. To a lesser degree, this is also true for phosphorus and sulfur.

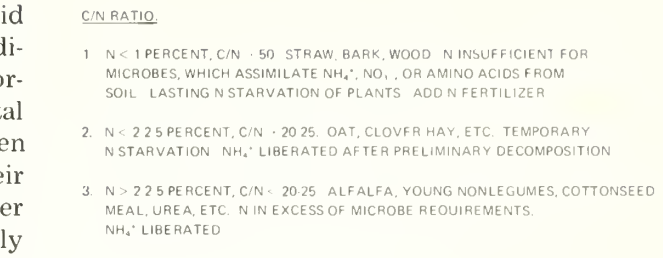

Figure 7. — Nitrogen relationships in organic matter decomposition.

Table 5. — Decomposition of -6 mesh wood and bark at 100 tons per acre in Branchville sandy loam soil[1]

Material	Carbon released as CO_2 in 60 days	
	Wood	Bark
	Percent	
Douglas-fir	11.2	10.6
Eastern hemlock *(Tsuga canadensis)*	7.5	6.1
Ponderosa pine	13.7	9.6
White pine *(Pinus strobus)*	16.4	3.6
White fir *(Abies concolor)*	16.2	10.4
Eastern redcedar	1.5	17.7
Incense-cedar	4.2	6.5
Redwood	3.8	2.1
Mean of 19 softwoods	12.8	8.8
Black walnut *(Juglans nigra)*	27.1	13.7
White oak *(Quercus alba)*	38.1	27.4
Wheat straw	54.6	

[1] *After Allison (1965).*

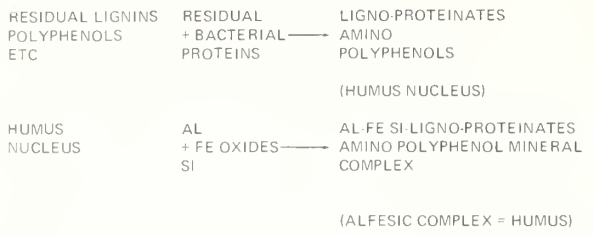

Figure 8. — Humus formation.

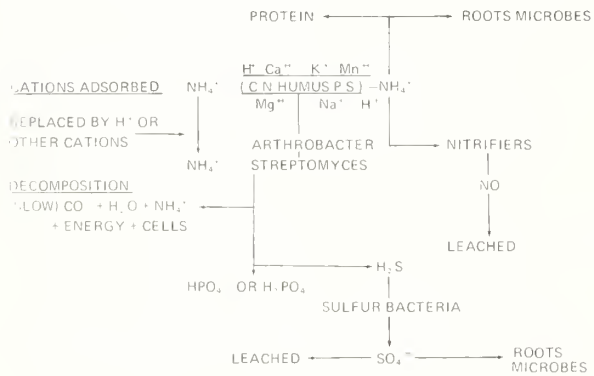

Figure 9. — Humus CEC and decomposition.

1. ALFALFA, DRIED BLOOD, PEPTONE, UREA, ETC.: C/N < 2-15. RAPIDLY DECOMPOSED. NH_4^+ LIBERATED
2. HUMUS, UF RESINS, LEATHER: N > 5 PERCENT, C/N < 0.5-10. DECOMPOSITION AND LIBERATION OF NH_4^+ SLOW, REGARDLESS OF N.

Figure 10. — Physical and chemical structure of organic matter in relation to N content and microbial decomposition.

Although different species of soil microbes have different quantitative requirements for food, the nutrient elements most extensively consumed in overall metabolism, other than oxygen and hydrogen, are carbon, nitrogen, phosphorus, potassium, and sulfur. Potassium is usually available in sufficient supply. The C:N:P:S ratios of total nutrients required by bacteria are approximately 50:1:0.5:0.1; i.e., for 50 parts C assimilated, 1 part N, 0.5 part P, and 0.1 part S are required for the overall metabolism. Soil nitrogen is most often a limiting nutrient in plant growth, and sometimes phosphorus and sulfur may also be deficient. With organic matter additions, therefore, supplemental phosphorus and sulfur should be considered in connection with soil type and kinds of plants to be grown.

Resistant lignins, resistant proteins, or other amino complexes of dead bacterial cells remain after the more susceptible components or organic matter additions have been decomposed. These residues combine with polyphenols to form a humus nucleus which absorbs iron, aluminum, and silicon oxides and becomes the complex known as humus or, as termed by Mattson (1948) (fig. 8), the Alfesic complex.

Humus, essential for soil tilth and fertility, represents a store of combined and sorbed nutrients. Typically, the C:N ratio is about 10:1. Nitrogen is slowly but continuously rendered available as ammonium by *Streptomyces* and specialized bacteria capable of attacking the resistant complex (fig. 9). Some of the soil nitrogen is in amino form, much of which in soil organic matter is not readily nitrifiable (Gupta and Reuszer 1961).

A high percentage of nitrogen in an organic material does not necessarily indicate it may be readily decomposed by microbes. Leather and urea-formaldehyde resins, as well as humus, have narrow C:N ratios, but their chemical or physical structure imparts high resistance to decay (fig. 10).

Effect of bark on plant growth

A former belief that tannins, resins, and other wood extractives have a toxic effect on plants when wood residues are added to soil has been found largely erroneous. We have learned from research that any "toxicity" noted after bark or other wood products are used on or in soil is most likely due to a nitrogen deficiency that can easily be remedied by adequate fertilization.

Extensive use of large proportions of various kinds of bark in container mixes for growing ornamental plants (Baker 1957, McNeilan 1967) attests to its favorable effects on plant growth. When adequate nutrients are supplied, especially nitrogen, plant growth in soil to which bark has been added is generally better than in corresponding unamended soil[13] (Bollen and Glennie 1961, Bollen and Lu 1957, Dunn 1956) (fig. 11, table 6). Yields were decreased without available nitrogen. Bark with added ammonium nitrate gave plant yields similar to those from unamended soil, but these were much less than from soil plus ammonium nitrate only. This finding emphasizes the assimilation of available nitrogen by microbes attacking the bark or wood.

In Willamette silty clay loam soil, Aspitarte[14] found that hot-water-extracted, Douglas-fir bark tannin liquor equivalent to 2,000 p.p.m. carbon was 33 percent decomposed in 60 days. On the same carbon basis,

[13] *See footnote 7.*

[14] *See footnote 7.*

Table 6. — Effect of bark, soil, and wood (sawdust) on yield of sunflowers on Willamette silt loam soil[1]

Treatment	Nitrogen content	C/N ratio	Yield (dry weight) average of three crops
	Percent		*Grams*
Soil only	0.16	16:1	84
Soil + NH_4NO_3 at 500 p.p.m. N	.21	12:1	109
Bark:			
Douglas-fir alone	.18	297:1	67
Douglas-fir + N	2.60	20:1	116
Douglas-fir composted	.25	221:1	86
Hemlock alone	.17	323:1	72
Hemlock + N	2.62	20:1	87
Wood (sawdust):			
Douglas-fir alone	.06	843:1	50
Douglas-fir + N	5.20	10:1	77
Hemlock alone	.06	841:1	54
Hemlock + N	5.20	10:1	75

[1] *1,500 grams soil per pot in greenhouse. Three replications. Organic additions at 10 tons per acre. N as* NH_4NO_3.

Figure 11. — Effect of bark and sawdust on growth of sunflower plants.

decomposition of wax amounted to 17 percent whereas only 8.5 percent of -20 mesh cork was decomposed.

Certain plant pathogenic fungi are inhibited and finally killed by tannin added to culture media (Cook 1911), probably by tanning the pectolytic enzymes (Williams 1963). Fungal mycelia are more tolerant than spores of the organism. Saprophytic fungi are less sensitive, and low concentrations of tannin appear stimulating, possibly serving as food. *Aspergillus niger*, a common soil mold, can thrive on tannin and has been used commercially to hydrolyze tannin to gallic acid (May and Herrick 1934).

According to Koch and Oelsner (1916), tannin is readily assimilated by soil molds, thus increasing the demand for ammonium and nitrate. Pine resin also was found to be utilized as an energy source. Tannin imparts a dark color to the soil, and large amounts harden the soil, presumably by precipitating colloids.

Certain cellulolytic bacteria are inhibited by tannins at 100 to 1,000 p.p.m., but the growth of others, except for changes in morphology, is only slightly affected (Henin et al. 1964). Shrikhande (1940) observed that fermentation of tea refuse was not impeded by the tannin complex, but the decomposition was qualitatively altered by selective action on the microflora. Plant virus transmission is inhibited by tannin, probably by action on the virus nucleoprotein (Cadman 1960).

Dihydroquercitin (Taxifolin), a flavonoid, occurs in bark and wood. In Douglas-fir bark, it amounts to as much as 8 percent of total dry weight, and in some Douglas-fir cork, it is more than 20 percent (Kurth 1951, 1953). Dihydroquercitin is believed to offer some decay resistance in lumber (Kennedy 1956) but is nontoxic to a wide variety of microbes and higher organisms.[15] Although small inhibition zones were found around crystals of the flavone placed on nutrient agar plates seeded with *Bacillus subtilis*, *Escherichia coli*, and *Staphylococcus aureus*, no toxicity was indicated by the phenol coefficient method.[16] At the same time, it was not utilizable by microbes as a carbon source.

Bark on the lower stem of Douglas-fir trees in moist locations is populated with numerous saprophytic molds to which the cork is resistant. Bark from ponded logs harbors many bacteria and other microbes. Freshly milled bark, unless completely dry, readily undergoes fermentation that generates heat; in large, self-insulated piles, this action may induce spontaneous combustion, as with sawdust. Extreme acidity also may develop.[17]

In laboratory experiments, finely ground bark decomposes rapidly in soil. For such studies, however, the bark is finely ground, usually -10 or -60 mesh, to allow intimate mixing with the soil sample. Surface exposure increases rapidly and microbial attack is facilitated as particle size is decreased. Allison (1965) found that during the first 30 days after soil treated with sawdust was exposed to microbial action, CO_2 evolution increased significantly with fineness of division of the particles. Thereafter, the differences between samples of -6, 10-20, and 20-40 mesh were within experimental error.

Regardless of mesh size, the screened product contains an assortment of particles ranging down to fine dust which will react most rapidly (fig. 4) (Neal et al. 1965). Results of decomposition studies must be interpreted with this fact in mind.

Bark is highly complex, physically as well as chemically. Douglas-fir bark, ground to pass 16 mesh, can be mechanically separated into the following percentages of different fractions: cork, -16+35 mesh, 25 percent; bast, -35+170 mesh, 25 percent; -170 mesh, fines and dust, 50 percent, consisting of broken cork and bast plus parenchyma and sieve cells. These components are decomposed in soil at different rates; -60 mesh cork was found to decompose more rapidly than bast or -60 mesh whole bark (Bollen and Glennie 1961). Less CO_2 evolved from the extracted young bark, suggesting a greater decomposability of the extractives. The water-extracted, old bark gave slightly more CO_2 than the unextracted, possibly indicating a

[15] *Personal communication from Dr. Harvey Aft, Forest Research Laboratory, Oregon State University.*

[16] *Bollen, W. B. Unpublished data. 1957.*

[17] *See footnote 11.*

water-soluble inhibitor. Of the mechanical fractions, the cork (-60 mesh) decomposed most rapidly, followed in order by bast (-35+170 mesh), fines (-170+250 mesh), and dust (-250 mesh). Larger particles (> −10 mesh) would decompose more slowly.

Gibbs and Werkman (1922) found that various sawdusts, incorporated at 100 to 300 tons per acre, slightly inhibited ammonification and nitrification in several different soils. All the sawdusts, except cedar, exerted very little inhibiting action on fixation of nitrogen in solution by *Azotobacter* (Gibbs and Batchelor 1928). Laboratory results have shown little retardation of ammonification and nitrification of peptone by Douglas-fir bark at 100 tons per acre, but nitrification of ammonium sulfate was inhibited (tables 7 and 8).

Water-soluble phytotoxins are produced under relatively high moisture conditions during decomposition of straw and other crop residues in soil (Toussoun et al. 1968). The phytotoxic effects of phenolics, which appear to be major components, decline after a few weeks. Similar soil toxins were recognized and extracted from soils many years ago (Schreiner and Shorey 1909). Fortunately, under aerobic conditions many soil organisms rapidly decompose such compounds (Gardner 1926). Bark is more resistant to decomposition than most other agricultural crop residues and should not be a serious source of phytotoxins, especially under anaerobiosis.

In climates where low temperature limits organic-matter decomposition, even when moisture is plentiful, soils of recently cleared coniferous timberlands may contain accumulations of toxic resins or pitch during the first few years of cultivation (Neidig and Snyder 1929). However, such accumulations do not occur in climates, such as that of western Oregon and Washington, where temperature and moisture are favorable to microbial action. Under optimum environmental conditions, finely divided Douglas-fir pitch is decomposed in soil as rapidly as straw (Bollen and Lu 1957) and pine resin also decomposes readily (May and Herrick 1934).

Bark decomposes slightly more slowly than sawdust. The bast fraction of bark is more resistant to decay than the cork fraction which contains tannins, dihydroquercitin, and other extractives that, by their nature, might be considered to be more or less toxic (Bollen 1959, Bollen and Glennie 1961). Glycosidal substances from bark of *Fraxinus* species have been reported to inhibit *Bacillus cereus* in vitro (Jung and Hubbes 1965). It is unlikely, however, that such inhibition would occur in soil, because antibiotics generally are susceptible to destruction by many soil organisms.

Tannins, plant polyphenols commonly used to convert animal skins to leather, range from 8 to 18 percent in Douglas-fir bark (Kurth et al. 1948, Kurth 1953). Tannin concentrations are highest in top logs of trees 50 to 80 years old. Bark from true firs contains comparable percentages but in mountain hemlock (*Tsuga mertensiana*), tannin concentration may be more than 20 percent (Kurth 1958). The following values have been reported for other species on the basis of 80-percent leaching efficiency: ponderosa pine, 6 percent; western larch (*Larix occidentalis*), 12.5 percent; and white fir, 8 percent (Jarvis 1963). It is thus evident that at rates bark would be applied, large amounts of tannins are introduced into the soil. Despite this, no toxic effects have been reported nor do they appear likely in view of the rapid decomposition of cork previously mentioned. However, tannins combine with proteins and reduce the rate of protein decomposition, as estimated from the production of carbon dioxide in liquid media inoculated with soil (Basaraba and Starkey 1966). Tannins alone decomposed more slowly than tannin-protein complexes, but even at 2-percent concentration, tannins were 12 percent decomposed in 18 days at pH 4 and 24 percent at pH 7. The inhibitory effect of tannins on plant residue decomposition is attributed to inactivation by tannin of microbial exoenzymes (Benoit and Starkey 1968).

Recent studies in our laboratory have shown that in each of two widely different soils, additions of purified tannin (tannin, 97 percent; sugars, 0.1 percent; ash, 2.07 percent; carbon, 55.69 percent; nitrogen, 0.12 percent) equivalent to 2,000 p.p.m. carbon were 22 percent decomposed in 180 days, as indicated by CO_2 evolution. At the same

time, the mold and bacterial populations were approximately doubled.

Western redcedar bark may be toxic to plants, although it is presently being used extensively for mulching in the Eugene, Oregon, area with no untoward results so far reported. Lunt and Clark (1959) found incense-cedar bark in a 50-50 soil mix to be slightly toxic. Allison (1965) found both bark and wood of incense-cedar to be toxic to garden peas. Wood of cedar, and to some extent that of redwood and western juniper (*Juniperus occidentalis*), contains thujaplicins and polyphenols which retard decay. Thujaplicins are water soluble and can be toxic to young roots on direct contact (Krueger 1968). Before use of such woods on plants, leaching of the material by copious irrigation is advisable.

Table 7. — Effect of -10+40 mesh Douglas-fir bark on nitrogen transformation in Woodburn silt loam soil

Treatment	N	Ammonification at 5 days	Nitrification at 30 days
	P.p.m.	*Percent*	*Percent*
Soil only	1,050	1	1
Soil plus additives:			
Peptone (15.8 percent N)	1,000	69	7
Bark (0.14 percent N) at 100 tons per acre	140	0	0
Bark plus peptone	1,140	58	6
Ammoniated bark (1.39 percent N) at 100 tons per acre	1,390	44	4

Table 8. — Effect of -10+40 mesh Douglas-fir bark and other additives on nitrification of $(NH_4)_2SO_4$ in Woodburn silt loam soil

Treatment	N	Nitrification at 30 days
	P.p.m.	*Percent*
Soil only	1,050	2
Soil plus additives:		
$(NH_4)_2SO_4$	200	20
$(NH_4)_2SO_4$ +$CaCO_3$ at four tons per acre	200	43
Bark (0.14 percent N) at 50 tons per acre	70	0
Bark + $(NH_4)_2SO_4$	270	2
Ammoniated bark (1.39 percent N)	200	5
Ammoniated bark (1.39 percent N) at 50 tons per acre	700	2

Agricultural uses of bark

Mulching

A mulch is any material placed on the soil surface primarily to prevent evaporative water loss or to suppress weed growth. Mulches also minimize temperature fluctuations in the plant root zone and prevent wind and water erosion of soil. Mulches have esthetic value, encourage earthworm populations, and improve the root environment for many plants.

Many different materials can be used for mulching: dust, stones, paper, plastic sheeting, asphalt emulsions, bark, sawdust, straw, and other crop residues. An ideal mulching material should be safe for plants and animals, pleasant and easy to apply, attractive, long lasting, noninjurious to soil microflora, and an eventual source of soil humus. An excellent review of mulches, their properties, effects, and selection for landscaping has been presented by Roberts (1968).

Bark is an excellent mulching material. It is superior to sawdust because it has a more pleasing color and texture and reflects less heat from its surface to the undersides of plants. It is also better than straw because it is more pleasing in appearance, longer lasting, less a fire hazard, and does not rapidly lose volume. Moreover, unlike most crop residues used for mulching, bark is free of weed seeds.

Size and distribution of ground bark particles is important to mulching use. There should be no excess of fines, which cause disagreeable dust in handling and may also cause compaction sufficient to retard aeration and infiltration of water. The ideal product is difficult to define, but a screened grind, ranging from one-half inch to fines with the majority of particles ranging from one-fiftieth to one-eighth inch (approximately 32 to 6 mesh), may be generally satisfactory. Particle-size distribution of two samples of milled bark and sawdust from different sources is shown in table 9. The mill-run sawdust sample has a desirable minimum of fines with fewer of the smaller fines.

Some bark, notably that of western redcedar and coast redwood, yields small particles that are long and fibrous. Hemlock bark contains a desirable assortment of particles, including those that are short and fibrous. Milled bark sometimes includes appreciable amounts of wood removed by cutter-head debarkers. Too much wood detracts from the appearance. Hemlock and white fir bark are more pleasant to handle than that of Douglas-fir, which has sharp, stiff bast fibers about 1 millimeter long. These can be quite irritating to the skin and in aggravated cases may even induce infection. However, they are not noticeable in ammoniated or composted bark, and pelletizing renders them innocuous.

Bark, as well as other organic mulches, eventually may incorporate with the soil and decompose, adding to the humus supply and improving the soil physically by increasing aggregation. Bark decomposition by microbes requires available nitrogen which, in wood residues, is nearly always very low (tables 2 and 3). If microbes attacking sawdust and bark do not find sufficient nitrogen therein, they absorb their requirement from the soil, thus competing with plant roots. Plant growth reduction as a result of this competition may be avoided by addition of nitrogen fertilizer to adjust the ratio of carbon:nitrogen to near 25:1.

The nitrogen addition (table 10) need not, however, be based on the total carbon content of the material because only part of the substance, 5 to 10 percent in the case of bark, is water soluble (table 11) and thus more readily available to attack by microbes than are the resistant lignocelluloses. In practice, it usually suffices to add 5 to 10 pounds of fer-

Table 9. — Particle-size distribution of bark and sawdust mulch samples

Mulch sample	Mesh designation, Tyler standard sieves									
	5	10	20	40	60	80	100	150	200	>200
	Percent retained on screen									
Bark:										
Douglas-fir (hammermilled)	2.6	20.3	20.0	17.7	15.7	8.0	4.2	4.0	3.6	4.3
Douglas-fir (hogged)	39.8[1]	29.4	9.5	13.1	2.9	1.7	.8	1.1	1.0	.2
Sawdust:										
Douglas-fir (mill run)	17.7	18.6	33.2	18.1	5.6	2.6	1.8	1.8	.7	.6
Douglas-fir (gangsaw)	0	29.3	40.9	23.3	3.3	1.3	.6	.5	.5	.2
Western hemlock (gangsaw)	0	30.3	41.7	20.9	3.6	1.3	.5	.5	.4	.3

[1] *>1/2 inch, 1.4 percent. <1/2 inch but >1/4 inch, 38.4 percent.*

Table 10. — Nitrogen fertilizer requirements for optimum decomposition of crop residues

Crop residue	Nitrogen content	Nitrogen required to raise N to 2-percent concentration
	Percent	*Pounds per ton*
Alfalfa	2.40	0
Green vetch	4.50	0
Barley hay	1.20	16
Corn stalks	.90	22
Barley stubble	.60	28
Western hemlock bark	.27	35[1]
Douglas-fir bark	.12	38[1]

[1] *Major constituents are resistant to decomposition. Thus, only 5 pounds per ton is required to satisfy N demand of water-soluble materials.*

tilizer nitrogen to each ton, dry basis, of mulch at the time of application. About 2½ to 5 pounds of nitrogen per ton should be added the second year to care for the more slowly decomposable constituents. After this, no further nitrogen additions should be required; the nitrogen previously assimilated by microbes will be released following their death and will become available for succeeding generations. Such repartition and reassimilation will not occur unless plant demands and leaching losses are compensated.

The foregoing rule for applying supplemental nitrogen to an organic mulch can be safely applied only in the case of moderately thick mulches. A 1-inch bark mulch weighs approximately 20 tons per acre, ovendry basis. At the suggested rate of fertilizer application, 500 to 1,000 pounds per acre of ammonium sulfate (21 percent N), or the same nitrogen equivalent of another form of fertilizer, would be required. Adequate irrigation after heavy applications of nitrogen fertilizer will avoid salt injury to plants.

Deep mulches of bark or sawdust, with appropriate fertilizer additions, are considered almost essential in the successful culture of blueberries and certain ornamentals such as azaleas and rhododendrons on mineral soils in Oregon. Thick mulches which, for crops such as blueberries, may be maintained at a depth of 4 to 6 inches when fully settled, require addition of fertilizer in increments judiciously timed with irrigation needs. In actual mulching practice, additional bark or sawdust is applied every other year at a rate of about 1 inch to compensate for settling and decomposition (Roberts and Mellenthin 1959). Relatively little of the thick mulch is in contact with the soil at any time, so little additional fertilizer nitrogen is required in any one year until plant roots extend into the mulch.

Nitrogen added to an organic mulch must be regarded only as food for the microbes decomposing the mulch; nitrogen required for plant nutrition is an additional demand. To a lesser extent, soil microbes also demand available phosphorus and sulfur. In some soils, these nutrients may be limiting to microbial and plant growth and should be supplied by appropriate fertilizing.

Organic mulches decompose mainly at the zone of contact between the underside of the mulch and the mineral soil surface. Mulching

Table 11. — Analysis of cold-water solubles in bark, wood, and moss peat

Species	pH		Water soluble[1]		Kjeldahl nitrogen		C/N ratio	
	Bark	Wood	Bark	Wood	Bark	Wood	Bark	Wood
				Percent				
Western redcedar:								
Untreated	3.2	3.5	2.95	6.99	0.14	0.06	378:1	810
Extracted	4.5	4.6	--	--	.13	.06	392:1	835
Redwood:								
Untreated	3.2	4.4	2.35	1.67	.11	.07	473:1	753
Extracted	4.8	5.6	--	--	.11	.06	457:1	876
Red alder:								
Untreated	4.6	5.8	11.64	1.43	.72	.13	71:1	377
Extracted	5.0	6.0	--	--	.81	.15	62:1	320
Western hemlock:								
Untreated	4.1	6.0	3.95	3.47	.27	.04	212:1	1,234
Extracted	4.4	4.4	--	--	.24	.03	223:1	1,618
Ponderosa pine:								
Untreated	3.8	4.4	4.35	2.68	.12	.04	422:1	1,297
Extracted	3.9	4.2	--	--	.13	.06	429:1	895
Sitka spruce:								
Untreated	4.9	4.1	10.89	1.27	.41	.04	130:1	1,214
Extracted	6.4	6.4	--	--	.40	.04	127:1	1,194
Douglas-fir:								
Untreated	3.6	3.4	5.49	4.65	.12	.04	471:1	1,268
Extracted	3.8	3.3	--	--	.11	.04	513:1	1,242
Sour sawdust	--	2.0	--	12.81	--	.06	--	893
Moss peat:								
Untreated		3.8		1.04		.83		58
Extracted		4.4		--		--		--

[1] *Total solids in 12 successive 1:10 water extractions, 24 hours each.*

materials low in nitrogen may reduce available nitrogen in this contact zone and thus encourage nonsymbiotic nitrogen fixation by *Azotobacter* and certain species of *Clostridium*. In this way, some of the nitrogen deficiency may be relieved.

Other properties of mulching materials requiring some consideration are bulk density, heat capacity, and reflectance. Bulk density varies with particle size and distribution; fines increase the density. Agricultural grades of ground bark are heavier than moss peat but lighter than sawdust. Ground bark, which typically includes large particles minimizing the tendency to pack, is favorable to infiltration of water.

The heat capacity of an organic mulch depends largely upon its water content. Bark can hold water in amounts several times its weight, in some cases even more than wood of comparable particle size (table 12). Air-dry bark is also difficult to wet (table 13), depending on particle-size distribution and tree species from which the bark came.

The color of a mulching material is important. Sawdust, generally light colored and smooth textured, reflects heat which may cause sun scald of low leaves and fruit. Bark is darker than sawdust so it absorbs light and heat more readily and also loses moisture more rapidly because of evaporation induced by absorbed heat.

Mulches importantly affect soil microclimate (Roberts 1968) through their insulating properties. In the presence of a mulch, the rate of heat exchange is reduced as is also total heat conducted to the soil surface during the day and that released from the soil to the atmosphere at night. A mulched soil surface provides a cool root medium for plants growing in exposed locations during hot weather. However, use of a mulch can expose plants to so-called radiation frost in fall and spring when heat loss from soil to atmosphere may be a critical requirement for plants that have not developed adequate cold resistance.

For meaningful calculations, in determination of the fertilizer requirements for an application of bark volume weight data on the ovendry (105° C.) basis are essential, but no precise information is to be found in the literature. Various papers, trade brochures, and letters [18] give weights ranging from 9.7 to 30.6 pounds per cubic foot for ovendry Douglas-fir bark. These differences must be due to variations in particle size and compaction. A weight of 3,000 pounds per unit, or 25 pounds per cubic foot, has been mentioned for hogged bark, species and water content not indicated. For bagged bark, 18 pounds per cubic foot has been suggested.

Thin mulches are useful where soil crusting prevails. Tests with Loamite,[19] placed over planted seeds of broccoli, lettuce, celery, aster, and other plants, have shown plant emergence increases 40 to 80 percent over unmulched seedbeds. Higher emergence rates permit planting fewer seeds, thus reducing thinning labor (Ellis 1965). Seedlings in treated areas also emerge earlier in the season. Seedlings in treated areas also emerge earlier in the season. Bark of approximately —10 mesh size may also favor seedling emergence. Light dressings of bark are also extensively used on newly seeded lawns.

Thick mulches of bark are excellent for blueberries, raspberries, and orchards, and give better results than straw (Latimer 1956, Roberts 1968). An initial bark application 8 to 10 inches thick, as sometimes applied on orchard soils, should last about 10 years. The advantages would be in weed control, moisture retention, elimination of cultivation, and year-around use of orchard equipment. The mulch also frees the top soil moisture and nutrients for tree use and prevents root damage that often results from cultivating bare soil.

Soil Conditioning

Incorporating bark or other organic matter physically benefits soil. Fine-textured or heavy soils are rendered more porous, which may improve aeration and drainage. This action results not only from soil dilution — the mechanical intermixing of bark particles with soil — but also from subsequent decom-

[18] *Summary of information concerning weight and volume of bark. R. A. Currier. Forest Research Laboratory, Oregon State University, Corvallis, Oregon. Mimeogr., 3 pp., [n. d.] Privately distributed.*

[19] *A soil amendment-fertilizer manufactured from sawdust by the Fersolin Corp., associate of Pope & Talbot, Inc., San Francisco, Calif. (Farber and Hind 1959) (fig. 3).*

Table 12. — Water-holding capacity of bark, wood, and moss peat, by species and mesh[1] size

Species	Bark		Wood	
	−10+40	−40	−10+40	−40
	Percent ovendry weight			
Douglas-fir[2]	283	340	330	440
Hemlock	307	368	273	614
Ponderosa pine	324	566	243	665
Sitka spruce	159	215	616	998
Redcedar	584	490	393	658
Coast redwood	500	400	320	356
Red alder	277	270	418	627
Moss peat	765	450	--	--

[1] *See text footnote 12.*

[2] *A 25-millimeter cube of bark had a water-holding capacity of 60 percent; a −5 mesh sample of wood had a capacity of 228 percent.*

Table 13. — Relative wettability of bark and wood of various species and mesh[1] sizes while being stirred in water[2]

Species	Bark		Wood	
	−10+40	−40	−10+40	−40
Red alder	3	2	3	2
Douglas-fir	2[3]	1	3	3
Hemlock	3	2	3	3
Ponderosa pine	3[3]	3	3	3
Sitka spruce	3	3	4	4
Redcedar	2	2	3	3
Coast redwood	2	2	3	3
Moss peat	3	2	--	--

[1] *See text footnote 12.*

[2] *1, very slowly; 2, slowly; 3, rapidly; 4, very rapidly.*

[3] *Except cork.*

Table 14. — Cation exchange capacity (CEC) of some organic residues and soils

Material	Mesh size[1]	CEC
		Meq./100 g.
Douglas-fir:		
Bark	+5	44.8
Bark	−10+40	39.7
Bark	−40	60.5
Wood	−10+40	39.5
Wood	−40+100	28.2
Wood	−100+200	15.0
Red alder:		
Bark	−10+40	40.4
Wood	−10+40	59.0
Wood	−100+200	7.5
Ponderosa pine wood	−10+40	13.5
Humin[2]		38.8
Wheat straw	−10	39.4
Wheat straw	−60	19.4
Moss peat	−10	120.6
Delhi loamy sand	−10	2.7
Walla Walla silt loam	−10	18.6
Chehalis silty clay loam	−10	24.3

[1] *See text footnote 12.*

[2] *Residue from treatment of wood waste with hydrochloric acid in the manufacture of levulinic acid by Crown Zellerbach Corp.*

position products and humus formation, which increase aggregation or granulation and thus improve tilth. Organic matter additions to coarse-textured soils increase their capacity to hold water in a form available to plants. Amount of organic additions to soil, however, must be controlled. Excessive additions may increase aeration so much that during hot weather the soil will dry at an undesirably rapid rate. Under wet conditions, increasing the water-holding capacity of soil unduly may result in waterlogging and development of anaerobic conditions.

Cation exchange capacity (CEC) is appreciably increased. This is especially important in sandy soils and others low in humus. Ammonium, as well as other cations, is held against loss by leaching but is still available to plant roots and microbes. The CEC of ground bark may be two to three times greater than that of a silt loam soil (table 14). Phenolic acid polymers in bark have neutralization equivalents of about 100 to 200 milliequivalents to 100 grams. Uronic acid substances, in both wood and bark, have a CEC as high as 100.

Much that has already been said concerning mulches applies also to incorporation of bark with the soil. Adding supplemental nitrogen to organic matter is even more important with soil incorporations because the bark is mixed with the soil and offers close contact with plant roots. Microorganisms are more effective than plant roots in obtaining needed nitrogen. For this reason, the rate of supplemental nitrogen should be about twice that used for mulches; i.e., 10 to 20 pounds nitrogen per ton of bark to bring the C:N ratio to near 50:1.

As much as 100 tons per acre of bark may be used in soil conditioning. This amount corresponds to a layer 4 to 5 inches deep before mixing, or to a 10-percent addition, by weight, to a plow depth of 6-2/3 inches, equivalent to 2,000,000 pounds of mineral soil. Disking is preferred to plowing as a method of incorporation; it ensures better mixing and leaves some bark on the soil surface as protection against erosion.

Addition of organic matter to the soil surface, or in various degrees of incorporation, dilutes the soil. This immediate or gradual physical dilution can improve aeration of heavy soils and increase the water-holding capacity of light soils. Although mulches do not immediately dilute the soil, in wet climates or under irrigation deep mulches may hold enough excess water to impede aeration and create problems associated with denitrification, anaerobic respiration, and the development of certain root rot organisms (Roberts and Mellenthin 1959). These hazards are most likely to develop on heavy soils. Soil type, therefore, must be considered in the use of mulches.

In our laboratory, ovendry Douglas-fir bark in one piece 5 inches thick by 6 inches by 11 inches from an old-growth tree weighed 38.7 pounds per cubic foot. This compares with 34 pounds for air-dry (water content 12 percent) Douglas-fir lumber, or about 30 pounds per cubic foot, ovendry (Institute of Forest Products 1957). The actual weight of bark or sawdust mulch per acre-inch varies greatly according to water content, species, mechanical analysis, and degree of packing. For calculating field applications of ground bark, a value of 11 pounds per cubic foot or 20 tons per acre-inch is suggested to represent the ovendry weight. The actual weight of sawdust applied to soils is likewise difficult to determine from various published reports. A close approximation for mill-run Douglas-fir sawdust is 10 pounds per cubic foot or 18 tons per acre-inch, ovendry basis.

Weights of 1 cubic foot of several brands of bagged bark purchased on the local market and for sawdust from a pile used for mulching are shown in table 15.

All the bark contained wood particles, mostly slivers, the larger of which to some extent detracted from its appearance. Although it is not economically feasible to avoid all wood slivers, etc., they should be kept to a minimum by appropriate screening. Note in table 15 that the Douglas-fir bark had lowest percentage of +5 and -5+10 fractions and contained the lowest percentage of wood.

Soil Mixes

Soil mixes containing relatively large fractions of organic matter and inorganic amend-

Table 15. — Water content, weight, and particle-size distribution of commercially prepared ground bark and sawdust

Property	Douglas-fir bark	Douglas-fir and hemlock bark, mixed	Hemlock bark	Douglas-fir sawdust, mill run
Water (percent)	66.7	88.8	80.2	73.9
Weight per cubic foot (pounds):				
Wet	17.8	20.7	20.1	16.9
Ovendry (105° C.)	10.7	11.0	11.2	9.7
Mechanical analysis[1] (percent of total):				
+5 mesh	4.4	26.1	20.0	6.3
−5+10 mesh	12.0	22.0	24.4	24.6
−10+40 mesh	36.6	32.8	36.0	62.1
−40 mesh	47.0	19.1	19.6	7.0
Wood particles (percent of total):				
+5 mesh[2]	1	2	2	20
−5+10 mesh[3]	10	5	5	10
−10+40 mesh[4]	1	5	10	5
Percent of total sample	2	3	5	7
−40 not determinable				

[1] *Determined on 200-gram ovendry samples after a mechanical shaking through Tyler standard sieves for 10 minutes.*

[2] *Mostly slivers about 1 to 2 inches long.*

[3] *Estimated — mostly slivers about 1 inch long.*

[4] *Estimated — mostly slivers about 1/2 to 3/4 inch long.*

ments are widely used for growing potted plants in nurseries and for special purposes in ornamental horticulture. Additions of organic matter such as moss peat, sawdust, and bark increase porosity, aeration, and water retention and decrease bulk density. Physical properties of these organic components and their influence on soil aeration and water relationships are most important (table 16). Low bulk density is desirable because it reduces handling effort and transportation cost of potted plants. Water conduction and retention properties are important to irrigation and control of salinity.

Water conduction and retention is determined by particle-size distribution and physical character of components and their combinations in the mix. A high water-holding capacity does not necessarily assure more available water; much of the water held requires more work or suction than the plant roots can exert (fig. 12, table 17) (Baver 1959, Feustel and Byers 1936, Lyon et al. 1950, Richards et al. 1964, Taylor 1965). Capillary water is optimum until at about 15 atmospheres tension the roots begin to have difficulty in absorbing water; wilting may

Table 16. — Physical properties of soil-mix components and some mixtures[1]

Soil components	Bulk density		Porosity	Moisture retention		Air space after drainage
	Dry	Wet				
	Pounds per cubic yard		*Volume percent*	*Volume percent*	*Weight percent*	*Volume percent*
Clay	1,585	2,505	59.6	--	59	4.7
Fine sand	2,400	3,050	44.6	--	27	5.9
Perlite, 3/16 to 1/4 inch	150	470	75.3	--	213	56.3
Vermiculite, 3/16 inch	182	1,077	80.5	--	492	27.5
Sphagnum peat	163	1,228	84.2	--	560	25.4
Redwood sawdust	296	1,126	77.2	--	280	27.9
Redwood bark, 3/8-inch mesh	210	725	80.3	--	245	49.5
Manure, dairy	580	1,630	74.3	--	182	7.6
Clay and fine sand	2,203	2,898	47.4	41.5	32	6.9
Clay and sphagnum peat	910	1,930	71.0	61.0	112	10.0
Fine sand and sphagnum peat	1,540	2,330	57.5	47.0	51	10.5
Fine sand and redwood sawdust	1,490	2,280	58.7	47.0	53	11.7
Fine sand and redwood bark	1,570	2,300	56.8	43.5	46	13.3

[1] *O. A. Matkin. Unpublished data. 1962.*

occur near 30 atmospheres. If the water is saline, osmotic tensions impose additional stress upon the plant. Adding organic materials and soil conditioners to soil generally decreases available water but increases infiltration and aeration. Only in coarse-textured soils do organic additions consistently increase available water. This is in contrast to humus or native soil organic matter, which is highly decomposed, stabilized, and intimately associated with soil particles, improving structure and providing more porosity favorable for holding available water.[20] It should be emphasized that the performance of an additive cannot be predicted solely on the basis of its inherent properties; the mixture must also be considered.

Richards et al. (1964) found that 30-percent additions of redwood and pine shav-

[20] *The sorptive capacity of bark has recently been used in Sweden to remove oil slicks from water surfaces. Pine bark powder spread on the water's surface absorbs the oil and forms clumps which can be collected and burned (Anonymous 1967). The technique has been refined to utilize sausage-shaped booms stuffed with bark; after the oil is absorbed, the booms can be used as fuel (Geraghty 1968). Silicone-coated sawdust also is useful in combating oil slicks. After absorbing oil, the sawdust sinks and the oil is subsequently decomposed by hydrocarbon bacteria.*

Table 17. — Relation of organic matter to water-holding capacity and availability of soil water[1]

(In percent)

Soil, sand, peat, and their mixtures	Water-holding capacity	Moisture equivalent	Wilting	Available water	
				Percent	Percent of water-holding capacity
Clay loam soil	44.3	20.2	7.1	13.1	30
Quartz sand	28.3	1.4	.57	.83	29
Moss peat	1,057.0	166.0	82.3	83.7	8
Reed peat	289.0	110.0	70.7	39.3	14
Half clay soil and half moss peat	114.0	31.0	14.5	16.5	14
Four-fifths clay soil and one-fifth moss peat	57.4	21.6	8.5	13.1	23
Half quartz sand and half moss peat	89.1	12.7	5.2	7.5	8
Four-fifths quartz sand and one-fifth moss peat	47.8	5.6	1.8	3.8	8

[1] *From Feustel and Byers (1936).*

Table 18. — Lime requirement and pH of soil, bark, and mixtures, before and after autoclaving[1]

Soil and mixture	pH[2]		Lime requirement[3]	
	Before	After	Before	After
			Pounds per ton	
Chehalis sandy loam	5.2	5.6	0.1	1.2
Douglas-fir bark	3.6	3.5	24	31
Douglas-fir sawdust	3.5	3.3	17	19
Soil plus 10 percent of bark	4.8	4.9	4	25
Soil plus 10 percent of sawdust	5.0	5.0	6	11

[1] *2 hours at 15 pounds p.s.i. (gage pressure).*

[2] *pH of soil determined on 1:5 water suspensions; pH of bark and sawdust determined on 1:20 water suspensions.*

[3] *$CaCO_3$ required to raise pH to 7.0.*

CLASSIFICATION OF SOIL – WATER–PLANT RELATIONSHIP

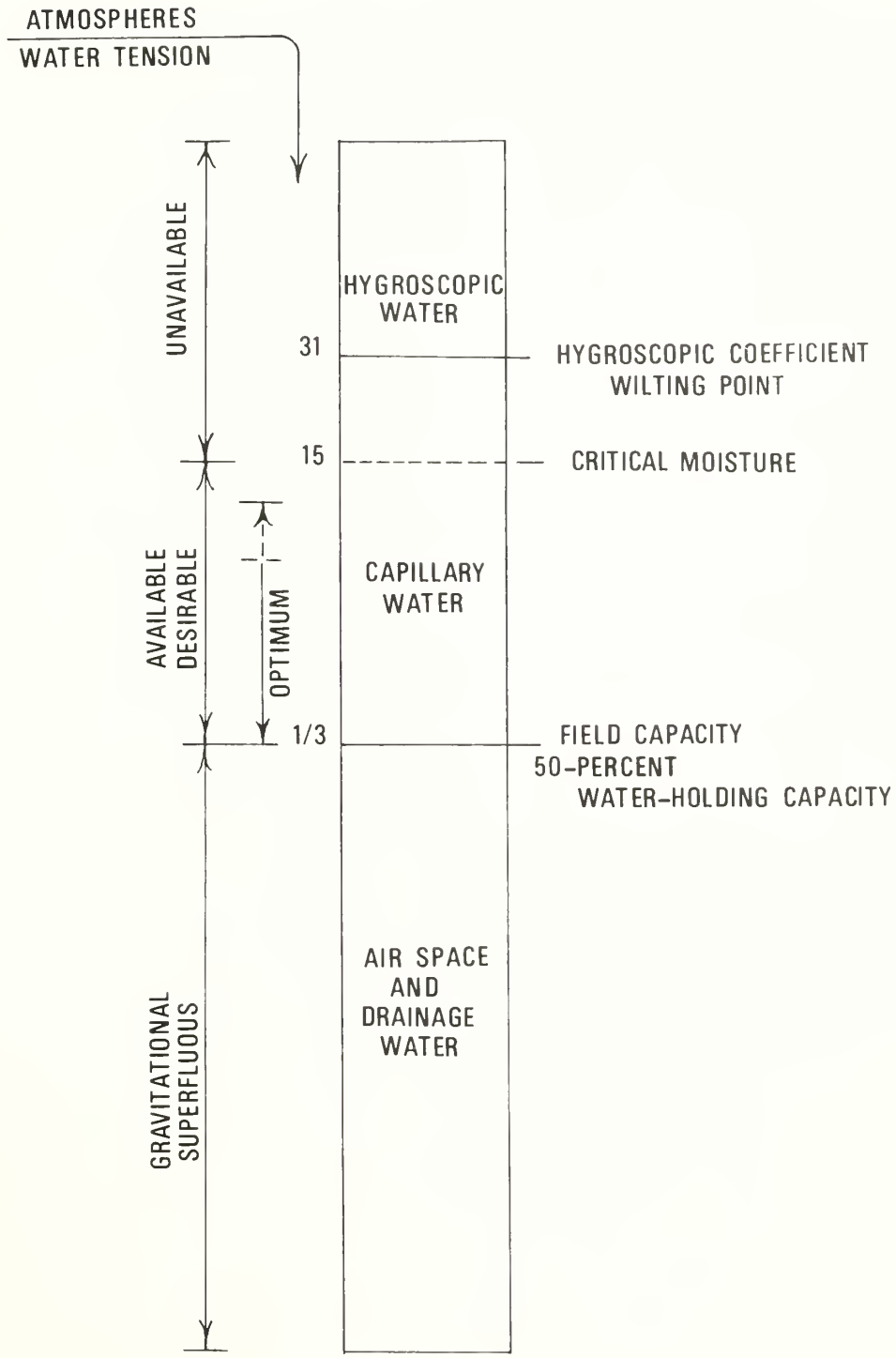

Figure 12. — Classification of soil-water-plant relationships.

ings in soil mixes increased water conductivity about five times; 60-percent additions gave increases near 20 times. Moss peat was much less effective. Water, released to plant roots by the mixture at low tensions up to 30 centibars (cb), approximately 4 atmospheres, was only slightly increased by the 30-percent additions; 60-percent additions about doubled the amount of water released. The amendments had little effect on release of water between 30 and 50 cb. Because of the limited amounts of water released above 30 cb, an irrigation program safe for potted plants should be based on irrigation when tensiometer readings reach 30 cb.

Fir, hemlock, pine, and redwood barks are often used in soil mixes in proportions as high as 50 percent (Baker 1957, McNeilan 1967). These artificial mixtures are used because they (1) permit standardization of physical, chemical, and biological properties of the media; (2) facilitate addition of formulated nutrients on schedule; and (3) are readily sterilized. Changes in pH and lime requirement due to sterilization by autoclaving may be important (Matkin et al. 1957). However, only small differences resulted when a sandy loam soil plus 10 percent Douglas-fir bark or sawdust was autoclaved (table 18).

Milled bark from loblolly and shortleaf pine, alone or mixed 50-50 with sand or perlite, is an excellent rooting medium for ornamental plants (Pokorny and Perkins 1967). Cuttings of some species rooted best in 100-percent bark (Pokorny and Gugino 1967). The bark also showed promise as an amendment for potting media and for container plants (Pokorny 1966).

Rooting of newly planted balled shrubs or trees can be benefited by backfilling the planting hole with a mixture of bark or other resistant organic matter and soil. Nitrogen fertilizer must be added as necessary. Loamite has been used in this way with much success in planting balled avocado and citrus trees (Anonymous 1963). The amended backfill is less likely to crack and settle and thus possibly break tender roots that venture from the ball. Aeration and water movement may also be improved.

Bark could replace sphagnum moss now used as a wrapping around tree seedlings planted on rocky sites (Hammer and Broerman 1967). With added fertilizer, an initial nutrient supply would be provided and, during dry periods, a reserve of moisture. The packaging may also give protection against possible adverse effects of herbicides used on the surrounding soil (Bickford and Hermann 1967). A 1:1 mixture of topsoil and moss peat appears advantageous for aiding survival of Douglas-fir seedlings on dry sites (Bickford and Hermann 1967).

Facilitating Drainage of Agricultural Land

Hundreds of thousands of acres of agricultural land require supplemental drainage to assure best crop growth. In this regard, a potential use exists for large tonnages of Douglas-fir bark as trench filler or backfill to overlay or substitute for tile in drainage ditches. Research on this use for bark is in progress in the Willamette Valley of Oregon.

Douglas-fir bark is especially suited for backfill purposes because fairly large, broken chunks free of fines are required to prevent drain clogging. When in place and covered with about 1 foot of soil, the bark would be more or less saturated with water most of the time. Under consequent anaerobic conditions, large pieces of bark would remain essentially undecomposed and should remain in place for many years.

Base Material for Composting Food Processing Wastes

Tremendous quantities of food processing wastes are now treated in stabilization ponds or sewage plants for disposal. Waste from poultry processing plants and canneries could be used for composting with bark, yielding a useful product and at the same time alleviating disposal and pollution problems. Suggestions for such use have been offered by Ivory and Field (1959).

Animal and Poultry Bedding

Bark is used increasingly as bedding in animal stalls, poultry houses, and stockyards because of the growing shortage of shavings and sawdust. After such use, the bark, now mixed and impregnated with manure, has premium value as a soil amendment and fertilizer.

Other uses of bark

Backfill for Septic Tank Drains

Another potentially large use for bark chunks is in preparation of septic tank drainfields. The method of use and drainage action is the same as described for agricultural land drainage.

Filter Bed Material for Effluent Disposal

Bark can be used as a substitute for stone or gravel in trickling filter beds for sewage and cannery effluent disposal. After use, the bark should be piled and allowed to stand until the slime decomposes. The product would be enriched with nitrogen and other nutrients derived from the sewage and also would be largely free of bark dust (Burton 1959).

Road and Highway Slope Stabilization

Bark has a potentially important use as a soil stabilizer for highway banks and other slopes. Economic application could be made with suitably designed hydraulic spreading equipment, such as is now widely used for applying straw and other organic materials to steep cutbanks and fills.

Ameliorating Forest Soil Properties After Timber Harvest

Main goals in good management of forest soils and watersheds include maintaining a protective organic cover on the soil surface, incorporating the maximum possible amount of organic matter with the soil, and providing maximum soil fertility. Bark, now removed from the forest on the log and transported to the mill to become a disposal problem, could be left at the logging site to contribute substantially to achieving the foregoing goals of good land management.

Portable machinery is now available[21] to remove bark and limbs from standing trees slated for harvest. Such machines are now used in Finland.[22] Benefits to be realized from the practice of leaving bark scattered over a logged area include not only those previously mentioned but also lowered log transportation costs and alleviation of air and water pollution associated with present methods of bark disposal.

Improving Water Quality in Municipal Watersheds

In certain soils, including some forested areas, nitrates accumulate during warm weather when moisture is favorable. Later, under heavy rainfall, the nitrates are leached into streams supplying water for domestic use, sometimes raising the nitrate concentration sufficiently to become a hazard to public health (Bormann et al. 1968). More than 10 p.p.m. nitrate nitrogen may induce methemoglobinemia in infants and is considered generally dangerous to human health (Lenain 1967).

By irrigating stands of oak and red pine with waste water from a sewage treatment plant, Pennypacker et al. (1967) found that quality of the effluent was much improved by removal of much of the phosphorus and ABS (alkylbenzenesulfonate, a hard detergent, resistant to biodegradation). Nitrates, although removed to a large extent in the underlying soil, increased twofold to threefold in the forest floor. It would seem that such nitrate buildup could be avoided by addition of bark to a watershed soil; microbes, attacking such an organic addition of wide C:N ratio, would assimilate the nitrate and thus prevent its leaching into water supplies.

Miscellaneous

Filler for commercial fertilizers.

Carrier or diluent for pesticides.

Eliminator of mud problems in barnyard and feedlots.

Ameliorator of salt conditions on alkali spots. A mulch would minimize buildup of salts on the soil surface.

[21] *Personal communication from H. P. Schneider, Forest Service Products, Inc., Wheaton, Ill.*

[22] *Personal communication from Dr. T. Norris, Sweden Forest Products Research Laboratory, Stockholm O. Sweden. 1968.*

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1969. Properties of tree barks in relation to their agricultural utilization. U.S.D.A. Forest Serv. Res. Pap. PNW-77, 36pp., illus. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

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A COMPUTER PROGRAM FOR EVALUATING FORESTRY OPPORTUNITIES UNDER THREE INVESTMENT CRITERIA

daniel e. chappelle

CIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
S. DEPARTMENT OF AGRICULTURE
S.D.A. FOREST SERVICE RESEARCH PAPER PNW-78

PORTLAND, OREGON
1969

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E R R A T A S H E E T

The following correction should be made to USDA Forest Serv. Res. Pap PNW-78, "A Computer Program for Evaluating Forestry Opportunities Under Three Investment Criteria," by Daniel E Chappelle:

On page 18, Table 1, IVST Program Input Format under "Item" entries for Input card types 7 and 8.

DELETE: "A second card is needed to handle 9-16 alternatives. A third card is needed to handle 17-20 alternatives."

INSERT: "Additional cards are required to read data for more than 8 periods."

Pacific Northwest Forest & Range
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1/ The rate-of-return computer programs devised by Hall (1962) and Forster (1968) are exceptions, since they are general and presume no particular problem context.

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INTRODUCTION

Researchers have provided forest managers and their consultants with several computer programs for analyzing investments in forestry (Hall 1962, Row 1963, Schweitzer et al. 1967, and Forster 1968). These computer programs have been modified in many cases to apply to situations not originally envisioned by the program developers (e.g., see Marty et al. 1966, Green and Alley 1967, Wikstrom and Alley 1968). These programs are particularly useful if the situation being analyzed fits one of the options available in the program and if the manager's investment criterion is handled by the program. However, most of the available computer programs are designed for specific problems and, therefore, are relatively complex to use.[1/] In addition, only two investment criteria are available in the programs; namely, internal rate of return and present net worth.

This paper is meant to fulfill the following objectives. First, to announce the availability of the IVST computer program to prospective users. Second, to discuss the applicability of this program to managerial problems. Finally, to outline the operating characteristics of the program so analysts can use it.

PROBLEMS WHICH MAY BE ANALYZED WITH IVST

IVST, in common with all other investment analysis computer programs, is designed to help the decisionmaker decide whether or not to pursue certain productive activities or alternatives. There are many types of investment decisions, including: (1) whether a certain kind of productive activity should be pursued at all, (2) the intensity at which a productive enterprise should be operated, (3) timing of the productive activity in relation to other activities, (4) sequence of the productive activity in relation to other activities, (5) the location at which the productive activity takes place, and (6) the best way to accomplish the productive activity--i.e., technology. Depending upon the way the alternatives are formulated, any decision may be included in an IVST analysis.

The type of decision to be analyzed dictates the kinds of data which are required. Here it is presumed that data will be expressed in economic units, e.g., dollars. Data will consist, therefore, of costs and returns tagged with a time dimension--date of occurrence. Realistically, the costs and returns must be regarded as managerial expectations, since an investment analysis of historical occurrences provides few guidelines to the future.

However, data alone are not sufficient to guide managers in their decision-making function. Also required is a decision rule or criterion, which simply stated is the manager's systematic way of evaluating how well alternative strategies provide for fulfilling the firm's goals.

Now, whereas the type of investment is completely open when IVST is used, the choice of criterion is not. Three alternative investment criteria are available in IVST: internal rate of return, present net worth, and benefit-cost

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[1/] The rate-of-return computer programs devised by Hall (1962) and Forster (1968) are exceptions, since they are general and presume no particular problem context.

ratio.[2/] It is the job of the manager to choose the criterion which will best provide for fulfillment of the firm's goals. If one of the three criteria available in IVST will fill this bill, then this computer program will be useful to the manager. On the other hand, if the manager selects an investment criterion that is not available in IVST, then the program will not be useful and, indeed, its use would be harmful, since misallocated resources would result.

IVST is a generalized computer program in that no particular problem context is presumed by its structure and output formats. The program is simple to use in that input requirements are minimal for the types of problems which may be analyzed. It is assumed that all preliminary data preparation is handled externally. Input data consist of a time-tagged stream of costs and returns and certain identifying information. A data preparation computer program will be required if data are in the form of quantities and prices. Large problems may be analyzed since data storage requirements are low per alternative analyzed. Finally, as pointed out above, IVST permits the analyst to select for examination one or more of three optional investment criteria: present net worth, internal rate of return, and the benefit-cost ratio. In addition, the structure of IVST is such as to permit other criteria subroutines to be added if desired by the analyst.

IVST was derived from two computer programs developed to analyze data for the Douglas-fir Supply Study, a cooperative study by the Pacific Northwest Region, Forest Service, and this Station. One of the computer programs was based on the internal rate-of-return criterion, the other on the present net worth and benefit-cost ratio criteria. These computer programs were modified to become options within IVST.

STRUCTURE OF IVST

IVST consists of a main program and two subroutines. The main program reads all data and provides for the printing of the first report, which consists of the input data. Subroutine BCA calculates the benefit-cost ratio and present net worth for the range of interest rates selected by the user. Subroutine IROR calculates the internal rate of return.[3/] All results of the analyses are printed under control of the subroutines. Either BCA and/or IROR may be selected for any problem by the analyst.

Both BCA and IROR are closed or linked subroutines, i.e., a subroutine not stored in the path of the main routine, IVST. A closed subroutine is entered by a jump operation in the main routine and return to the main routine is provided at the end of the operation. Because of this configuration, it is possible to

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[2/] The reader interested in the theoretical aspects of these economic criteria should consult Eckstein (1958, pp. 70-79) on the benefit-cost ratio, and Hirshleifer (1958, pp. 329-352) on the internal rate of return and present net worth criteria. A comparison of management guides developed by application of these criteria to a forestry problem may be found in Webster (1965).

[3/] Development of IROR began with a major modification of Row's rate-of-return program (Row 1963). The author wishes to acknowledge the programing assistance of Edgel E. Skinner of the Station's statistical and data processing services staff in this initial effort.

make use of the subroutines independently of the main routine. That is, the prospective user may design his own main routine and simply call either BCA and/or IROR when needed. It may be desirable to do this when input data are not in proper form for the present main routine. Prospective users are urged to consult a computer programer if the coding of a new main routine appears necessary.

If the user wishes output for all three criteria options, then a total of four reports will be printed. As noted above, the first report consists of the input data. In the second report, the benefit-cost ratio and present net worth for every interest rate within the selected range will be listed for each alternative. The third report consists of certain messages generated within the IROR subroutine that will assist the analyst in interpreting results of the internal rate-of-return analysis. Finally, the fourth report lists present net worth for each interest rate within the selected range for each alternative until the internal rate of return is found. The internal rate of return is listed as the last interest rate for each alternative. After the last report is printed, control is switched back from the subroutines to the main routine and an end-of-problem card is read. At that time, the user can either terminate the program or solve another problem.

The Main Program IVST

Function

The function of the main program is to read a stream of periodic annual costs, a stream of periodic annual returns, and associated data; prepare a report of the input data; generate annual costs and annual returns if data are for a period other than 1 year; and call in the criteria subroutines desired by the user. IVST is designed to accept periodic annual data for whatever period length the user desires. However, the same length period must apply to each cost and return entered for that particular problem. Of course, if period length differs from one alternative to another, each alternative may be run as a separate problem. If period length varies within an alternative, however, it is mandatory that period length be set at 1 year and that annual data be read.

The advantages of having the capability of reading periodic annual costs and returns, as opposed to annual inputs, include savings of time, card costs, keypunching costs, the minimization of input error, and convenience.

IVST permits initial costs and returns to be read when a period length of 1 year is designated. Initial costs and returns are those costs and returns that occur in year zero of the investment series.

IVST Inputs

There are 17 specific types of inputs to the IVST program. Formats of input cards are shown in table 1 of the Appendix. The inputs are:

1. Alphanumeric study identification.

2. Beginning interest rate of the range to be examined, decimal.

3. Final or ending interest rate of the range to be examined, decimal.

4. Increment in interest rate, decimal.

5. Number of alternatives in problem.

6. Indicator of an initial cost or return (i.e., a cost or return occurring in year 0). If initial costs and returns are used, then period length must be 1 year (i.e., annual data must be read).

7. Alphanumeric identification of alternatives.

8. Problem number.

9. Series type indicator (either terminable or perpetual).

10. Investment criterion indicator (either internal rate of return or benefit-cost ratio and present net worth, or all three).

11. Length of period over which periodic costs and returns apply, years. Annual data may be read by setting period length equal to 1.

12. Maximum number of years in any alternative, i.e., length of longest investment series of any alternative in the problem.

13. Number of years in each alternative.

14. Alphanumeric problem identification.

15. Periodic annual costs for each alternative, dollars.

16. Periodic annual returns for each alternative, dollars.

17. End of problem indicator.

IVST Main Program Outputs

Input items 1, 7, 8, 9, 11, 14, 15, and 16 constitute the first report of IVST (see fig. 1). Data for five alternatives are printed on each page.

INVESTMENT ANALYSIS-- RESEARCH PAPER SAMPLE PROBLEM

PROBLEM NO. 1 TEST DATA

TERMINABLE SERIES PERIOD= 5 YEARS

	MANAGEMENT ALTERNATIVE									
	ONE		TWO		THREE		FOUR		FIVE	
PERIOD	ANNUAL COST	ANNUAL RETURN	ANNUAL COST	ANNUAL RETURN	ANNUAL COST	ANNUAL RETURN	ANNUAL COST	ANNUAL RETURN	ANNUAL COST	ANNUAL RETURN
1	15	12	2266425	104294	32	34	33	91	65	12
2	23	65	2293ECC	25337	45	52	22	92	21	23
3	65	42	127557C	-74555	89	12	44	93	45	52
4	34	83	-21E6E55	1562245	78	65	55	94	23	45
5	0	0	-2214230	1584476	52	89	66	95	57	78
6	0	0	-2C31C94	1607694	14	35	88	96	84	65
7	0	0	C	C	65	67	77	97	52	98
8	0	0	C	0	23	85	22	98	11	63
9	0	0	C	0	15	64	11	31	32	65
10	0	0	0	C	24	13	22	32	11	32
11	0	0	0	0	57	25	44	34	44	12
12	0	0	C	C	62	35	66	35	55	45
13	0	0	C	0	54	53	88	36	22	78
14	0	0	C	C	13	92	99	37	33	96
15	C	0	0	C	52	45	33	38	65	32
16	0	0	C	C	C	0	55	39	47	58
17	C	0	C	C	C	0	45	32	0	0
18	0	0	0	C	C	0	23	45	0	0
19	0	0	C	C	C	0	15	68	0	0
20	0	0	C	C	C	0	72	28	0	0

Figure 1.--*First report of the IVST computer program showing input data.*

Subroutine BCA

Function

The function of subroutine BCA is to calculate present net worth and benefit-cost ratio for each alternative for the range of interest rates selected by the analyst.

Criterion

Present net worth of a terminable series of costs and returns (dollars) is:

$$PNW_n = \sum_{t=o}^{n} \frac{R_t}{(1+i)^t} - \sum_{t=o}^{n} \frac{C_t}{(1+i)^t} \qquad (1)$$

where

C_t = cost in year t, dollars[4/]

R_t = return or benefit in year t, dollars[4/]

i = discount rate, decimal

n = number of years in the investment series

Present net worth of a perpetual series of costs and returns is:

$$PNW_p = PNW_n \cdot \frac{(1+i)^n}{(1+i)^n - 1} \qquad (2)$$

In contrast, the benefit-cost ratio is:

$$\frac{B}{C} = \frac{\sum_{t=o}^{n} R_t / (1+i)^t}{\sum_{t=o}^{n} C_t / (1+i)^t} \qquad (3)$$

Equation 3 can be used for both terminable and perpetual series because the infinite series multiplier (the last term in equation 2) cancels out of equation 3.

Subroutine BCA does not assume that discounted returns (or benefits) or discounted costs are positive. It is likely that both negative returns and negative costs will occur if the analyst is working with marginal values (i.e., differences from some base).

[4/] Any asset salvage values (revenues) or replacement costs should be included in the last term of the series.

Four conditions are possible:

Condition	Return (or benefit)	Cost
1	+	+
2	-	+
3	+	-
4	-	-

Since the benefit-cost ratio must always be positive, it was necessary to include rules for conditions 2, 3, and 4 within the BCA subroutine. In conditions 2 and 3, the B/C is set equal to zero. In condition 2, the reasoning is that a negative return is equivalent to a positive cost, but returns are equal to zero, hence B/C = 0/+ = 0. Likewise, in condition 3 a negative cost is equivalent to a positive return, hence cost is equal to zero. Therefore, B/C = +/0, which is undefined. These two conditions can be easily discerned since condition 2 will always be associated with a negative present net worth, whereas present net worth will always be positive in the case of condition 3.

In condition 4, negative returns are equivalent to positive costs and negative costs are equivalent to positive returns, hence the benefit-cost ratio is set equal to its inverse, the ratio of costs to benefits (C/B).

In addition, it is possible that either discounted costs or discounted returns are equal to zero. In such a case, the BCA subroutine will set B/C equal to zero.

BCA Outputs

Subroutine BCA provides for printing the present net worth and benefit-cost ratio for each alternative for the entire range in interest rates, together with identification (see fig. 2).[5/] Results for five alternatives are printed on each page. After results are printed for all alternatives, control is returned to the main program.

Subroutine IROR

Function

The function of subroutine IROR is to calculate the internal rate of return for each alternative within a range of starting interest rates selected by the user, using the annual costs and annual returns generated by the IVST main program.

5/ The discounted costs and discounted returns may also be printed if the user so desires. The slight modification of the BCA subroutine which will provide this output is described in the Appendix, page 17.

BENEFIT-COST ANALYSIS-- RESEARCH PAPER SAMPLE PROBLEM

PROBLEM NO. 1 TEST DATA

BENEFIT-COST RATIO (B/C) AT ALTERNATIVE RATES OF INTEREST
PRESENT NET WORTH (PNW) AT ALTERNATIVE RATES OF INTEREST

	MANAGEMENT ALTERNATIVE									
	ONE		TWO		THREE		FOUR		FIVE	
RATE	*PNW	B/C*	*PNW	B/C*	*PNW	B/C*	*PNW	B/C*	*PNW	B/C*
0.	0.325CE 03	1.47	0.27C3E 0E	0.	0.455CE 03	1.13	0.1155E 04	1.24	0.9350E 03	1.28
0.5C	0.3032E 03	1.47	0.22C2E 0E	0.	0.3284E 03	1.12	0.1171E 04	1.31	0.7102E 03	1.26
1.0C	0.2832E 03	1.47	0.1765E 0E	12.19	0.2322E 03	1.10	0.1159E 04	1.3E	0.5356E 03	1.23
1.5C	0.264EE 03	1.46	0.1365E 0E	5.11	0.1588E 03	1.08	0.1136E C4	1.45	0.3991E 03	1.20
2.0C	0.247EE 03	1.46	0.1054E 0E	3.15	0.1026E 03	1.06	0.1090E 04	1.53	0.2915E 03	1.17
2.5C	0.2322E 03	1.46	0.7657E 07	2.23	0.5956E 02	1.04	0.1045E 04	1.61	0.2063E 03	1.14
3.0C	0.2178E 03	1.45	0.515CE 07	1.70	0.2650E 02	1.02	0.9984E 03	1.68	0.1383E 03	1.11
3.5C	0.2046E 03	1.45	0.2971E 07	1.36	0.1186E 01	1.00	0.9510E 03	1.75	0.8375E 02	1.07
4.0C	0.1923E 03	1.45	0.1078E 07	1.12	-0.1810E 02	0.98	0.9048E 03	1.81	0.3972E 02	1.04
4.5C	0.1809E 03	1.44	-0.5625E 06	0.94	-0.3268E 02	0.97	0.8605E 03	1.88	0.4019E 01	1.00
5.0C	0.17C4E 03	1.44	-0.1983E 07	0.81	-0.4355E 02	0.95	0.8184E 03	1.93	-0.2506E 02	0.97
5.5C	0.1606E 03	1.44	-0.3211E 07	0.72	-0.5152E 02	0.94	0.7789E 03	1.99	-0.4884E 02	0.94
6.0C	0.1516E 03	1.44	-0.427CE 07	0.61	-0.5717E 02	0.93	0.7419E 03	2.04	-0.6835E 02	0.91
6.5C	0.1432E 03	1.43	-0.5181E 07	0.54	-0.6101E 02	0.92	0.7075E 03	2.09	-0.8439E 02	0.88
7.0C	0.1354E 03	1.43	-0.5962E 07	0.48	-0.6335E 02	0.91	0.6754E 03	2.14	-0.9761E 02	0.85
7.5C	0.1281E 03	1.43	-0.6629E 07	0.43	-0.6464E 02	0.90	0.6457E 03	2.18	-0.1085E 03	0.82
8.0C	0.1213E 03	1.42	-0.7196E 07	0.39	-0.6499E 02	0.89	0.6180E 03	2.22	-0.1175E 03	0.79
8.5C	0.1150E 03	1.42	-0.7675E 07	0.35	-0.6463E 02	0.89	0.5923E 03	2.26	-0.1249E 03	0.77
9.0C	0.109CE 03	1.42	-0.E078E 07	0.32	-0.6373E 02	0.88	0.5685E 03	2.29	-0.131CE 03	0.74
9.5C	0.1035E 03	1.42	-0.8413E 07	0.30	-0.6241E 02	0.88	0.5462E 03	2.33	-0.1366E 03	0.72
10.0C	0.9834E 02	1.42	-0.866EE 07	0.27	-0.6076E 02	0.88	0.5255E 03	2.36	-0.1401E 03	0.70

Figure 2.--*Second report of the IVST computer program showing results of use of the present net worth and benefit-cost ratio criteria.*

Criterion

The internal rate of return (i) is defined as that interest rate which equates discounted returns to discounted costs, i.e., the rate that results in a present net worth of zero. If we use the same notation as above, then the internal rate of return is defined as i when the following condition is satisfied:

$$\sum_{t=o}^{n} \frac{R_t}{(1+i)^t} = \sum_{t=o}^{n} \frac{C_t}{(1+i)^t} \quad \text{for a terminable series} \tag{4}$$

or

$$\left[\sum_{t=o}^{n} \frac{R_t}{(1+i)^t}\right] \cdot \left[\frac{(1+i)^n}{(1+i)^n - 1}\right] = \left[\sum_{t=o}^{n} \frac{C_t}{(1+i)^t}\right] \cdot \left[\frac{(1+i)^n}{(1+i)^n - 1}\right] \tag{5}$$

for a perpetual series.

It should be noted that infinite series multiplier $\left[\frac{(1+i)^n}{(1+i)^n - 1}\right]$ cancels in equation 5, leaving it equivalent to equation 4. Therefore, the internal rate of return for a perpetual series is identical to the internal rate for a terminable series. However, discounted costs and returns will not be identical for both series.

At this point it may be helpful to indicate how the three investment criteria relate to one another. When the discount rate is equal to the internal rate and hence discounted costs are equal to discounted returns (present net worth is equal to zero), then the benefit-cost ratio is one (compare equations 1, 3, and 4).

Except for Forster's program (1968), all of the rate-of-return computer programs cited earlier use unmodified iteration to isolate the internal rate of return. In contrast, in IVST present net worth is iterated at interest rate intervals selected by the analyst until a change of sign is found. At that point,

the bisection method is applied until the internal rate of return is found within the interval at which the sign change occurs.[6] [7]

The power of this technique can best be realized by selecting a wide range of interest rates and a large value for the rate increment. In this way, convergence to the internal rate of return occurs quickly as large bisection intervals are used.

However, if one desires to calculate present net worth and the benefit-cost ratio as well as internal rate of return, the advantage of selecting a wide range of interest rates and a large value for the rate increment may be lost. The analyst will generally wish to use the BCA subroutine with a small value for the rate increment. This in turn may necessitate investigating a narrow range of interest rates (see program limitation 8, page 14). Because interest rates to be used in both subroutines are determined in the main program, they must represent a compromise if the two subroutines are to be used together. Therefore, in cases such as this, the analyst may prefer to use the subroutines sequentially. This can be accomplished by setting up two problems for a single computer run, both with identical data except for interest rate range and increment. One of the problems would be run with the IROR subroutine with a wide range of interest rates and large increment, and the other problem would be run with the BCA subroutine with a narrow range of interest rates and a small increment.

An example which illustrates the bisection method utilized in IROR is shown in figure 3. In this example a range of interest rates of 0 to 10 percent at increments of 5 percent were specified. The program calculated the present net worth (PNW) at a rate of 0 percent and found it to be $455. Next PNW was calculated at 5 percent and found to be -$43. At this point, the change in sign initiates the bisection procedure. The program calculates PNW halfway between 0 percent and 5 percent, that is at 2.50 percent. Here PNW is positive ($60), so the program tries the rate midway between 2.50 percent and 5 percent, or 3.75 percent. PNW at that rate is negative (-$9), so it is apparent that the internal rate lies between 2.50 percent and 3.75 percent. This procedure is continued until the internal rate of return is found at 3.52 percent on the sixth bisection (see fig. 3).

IROR Outputs

Three types of messages may be generated prior to the printing of tables showing the internal rate of return (see fig. 4).

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[6] For a discussion of the use of the bisection method for finding a real zero, see Hamming (1962, p. 352). The bisection method can result in both decreased computation time and increased accuracy. As Hamming points out, "Since each step halves the interval in which the zero lies, ten steps will reduce the interval by a factor of about 1,000; 20 steps, 1,000,000; etc. Thus the method, which assumes *only* continuity and the ability to evaluate the function at any point, is fairly effective."

[7] The recent rate-of-return computer program developed by Forster (1968) also utilizes the bisection method, which he terms "interval halving."

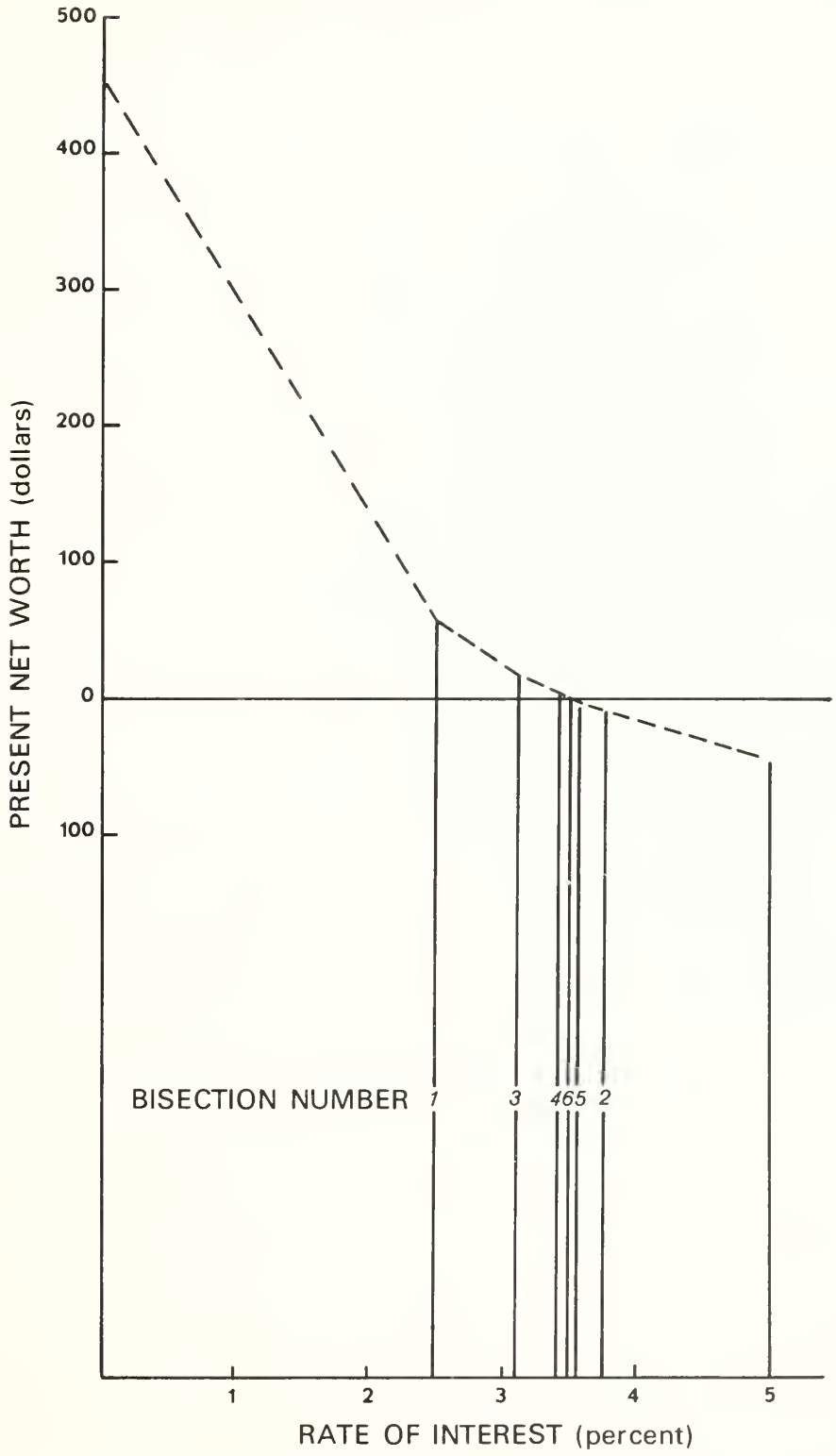

Figure 3.--*An example of how the IROR subroutine converges to the internal rate of return.*

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                DETERMINING RATE OF RETURN--      RESEARCH PAPER SAMPLE PROBLEM

PROBLEM NO.  1      TEST DATA

                                MESSAGES

    INTERNAL RATE OF RETURN DOES NOT FALL WITHIN SELECTED RANGE FOR ALTERNATIVE   1

    BISECTION LIMIT EXCEEDED IN ALTERNATIVE   TWO
    CALCULATED PRESENT NET WORTH DOES NOT FALL BETWEEN PLUS AND MINUS   1.00 DOLLARS

    PNW AS A FUNCTION OF INTEREST RATE IS NOT TENDING TOWARD ZERO WITHIN A PORTION OF ITS RANGE FOR ALTERNATIVE   4
```

Figure 4.--*Third report of the IVST computer program indicating messages generated by the IROR subroutine.*

If the internal rate of return is not found within the range of interest rates selected by the analyst, the message

> INTERNAL RATE OF RETURN DOES NOT FALL WITHIN SELECTED RANGE FOR ALTERNATIVE X

will be generated, with the alternative number filled in in place of X.

The second message that may be generated informs the user of the precision levels that apply to the internal rates of return. Precision level is indicated only when bisection is used. If the internal rate is found on iteration, a zero will appear in the PNW column and the precision level is to the nearest $0.01.

Three precision levels are built into the bisection phase of the IROR subroutine, $1, $10, and $100 (i.e., rate-of-return equation identity may be correct either to the nearest $1, $10, or $100). Up to 100 bisections may occur within each of these precision levels. Whenever an internal rate fails to be determined at one of these precision levels, a message is generated and the next lower level of precision is tried. The message is of the form

> BISECTION LIMIT EXCEEDED IN ALTERNATIVE X. CALCULATED PRESENT NET WORTH DOES NOT FALL BETWEEN PLUS AND MINUS Y DOLLARS

with the alternative number filled in by IROR in place of X, and the precision level in place of Y.

A third message will be generated whenever present net worth as a function of interest rate does not converge toward zero. In this case, the form of the message is

> PNW AS A FUNCTION OF INTEREST RATE IS NOT TENDING TOWARD ZERO WITHIN A PORTION OF ITS RANGE FOR ALTERNATIVE X

Occurrence of this message does not necessarily mean that the internal rate of return does not fall within the range of interest rates selected by the user. However, IROR will discontinue searching for the internal rate whenever the above condition is encountered. When this condition occurs, the analyst is advised to use the BCA subroutine to generate sufficient points to indicate the form of the present net worth function. If the above condition is caused by portions of the function which are not monotonic, it is likely that the interest rate range can be modified so as to exclude such portions, thereby permitting IROR to converge to the internal rate of return.

The behavior of IROR in various situations is illustrated in figure 5, wherein 10 representative types of present net worth functions are depicted.[8/] The types shown in figure 5 by no means exhaust the possibilities. In each graph, present net worth (dollars) is plotted over the range of interest rates selected for examination. IROR will treat each type of function as follows:

Type 1.--Present net worth is a monotonic decreasing function of interest rate. The internal rate of return falls within the range selected and will be determined by IROR.

Type 2.--Present net worth is a monotonic increasing function of interest rate. The internal rate of return falls within the range selected and will be determined by IROR.

Type 3.--Present net worth is a monotonic decreasing function of interest rate. However, the internal rate of return is located outside the range selected.

Type 4.--Present net worth is a monotonic increasing function of interest rate. However, the internal rate of return is located outside the range selected.

In the case of types 3 and 4, IROR will calculate present net worth for the full range of interest rates and then generate the message

> INTERNAL RATE OF RETURN DOES NOT FALL WITHIN SELECTED RANGE FOR ALTERNATIVE X

Type 5.--Present net worth is a monotonic decreasing function of interest rate. The internal rate of return is located outside the range selected, and present net worth is not converging toward zero as interest rate increases.

Type 6.--Present net worth is a monotonic increasing function of interest rate. The internal rate of return is located outside the range selected, and present net worth is not converging toward zero as interest rate increases.

In the case of types 5 and 6, IROR will calculate two iterated points along that segment and then print the message

> PNW AS A FUNCTION OF INTEREST RATE IS NOT TENDING TOWARD ZERO WITHIN A PORTION OF ITS RANGE FOR ALTERNATIVE X

Types 7 and 8.--Present net worth is not a monotonic function of interest rate. Although the internal rate of return lies within the range of rates selected, IROR will not determine it. Rather, these situations will be handled by IROR exactly as types 5 and 6. If these types of functions are suspected, the analyst should examine PNW over a wide range of interest rates by use of BCA subroutine. After examining BCA outputs, it is possible to reset the range in interest rates to avoid the program stop, thereby permitting the IROR subroutine to converge to the internal rate of return. Also, it should be pointed out that

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[8/] Samuelson (1937, p. 475) indicates that some investment opportunities may have no real internal rate of return (i.e., the present net worth equation has only imaginary roots). Also, he mentions the possibility of multiple internal rates, i.e., the present net worth function may equal zero at many interest rates.

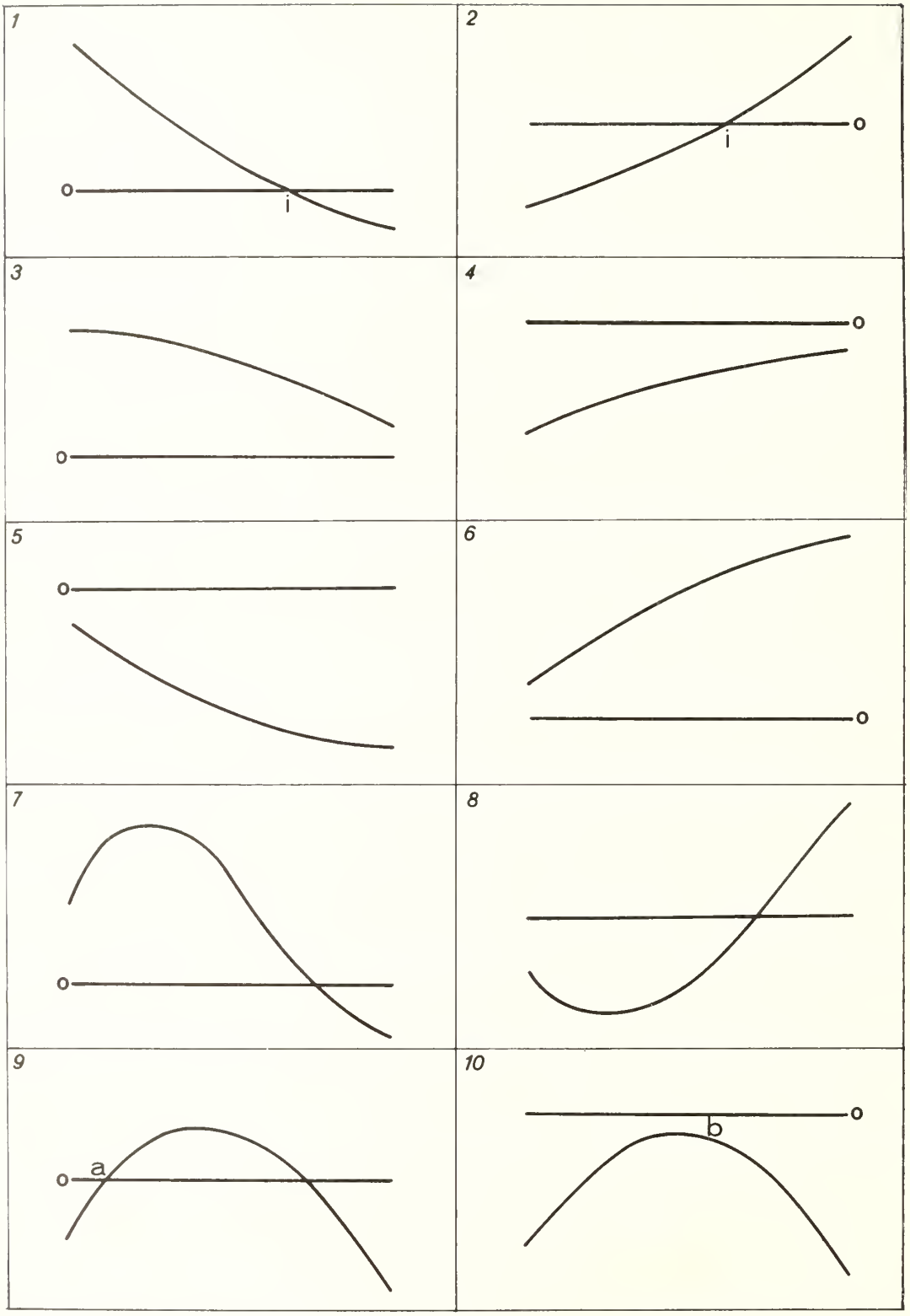

Figure 5.--*Representative types of present net worth functions.*

if the analyst initially sets the interest rate increment large enough, the program stop may be avoided and convergence will occur.

Type 9.--Present net worth is zero at two interest rates. IROR will locate only point a.

Type 10.--Points will be iterated until point b is reached, at which time the following message is printed and the program proceeds to the next alternative.

> PNW AS A FUNCTION OF INTEREST RATE IS NOT TENDING TOWARD ZERO
> WITHIN A PORTION OF ITS RANGE FOR ALTERNATIVE X

The final output is a table listing interest rates and present net worths for each alternative until the internal rate of return is reached (see fig. 6). When the internal rate of return is found, the precision level applicable to that rate is indicated in the present net worth (PNW) column.

DETERMINING RATE OF RETURN-- RESEARCH PAPER SAMPLE PROBLEM

PROBLEM NO. 1 TEST DATA

PRESENT NET WORTH (PNW) AT ALTERNATIVE RATES OF INTEREST

MANAGEMENT ALTERNATIVE

ONE		TWO		THREE		FOUR		FIVE	
* RATE	PNW *	* RATE	PNW *	* RATE	PNW *	* RATE	PNW *	* RATE	PNW *
0.	3.2500E 02	0.	2.7029E 07	0.	4.5500E 02	0.	1.1550E 03	0.	9.3500E 02
0.50	3.0322E 02	0.50	2.2019E 07	0.50	3.2838E 02	0.50	1.1709E 03	0.50	7.1018E 02
1.00	2.8318E 02	1.00	1.7654E 07	1.00	2.3221E 02	0.	0.	1.00	5.3560E 02
1.50	2.6477E 02	1.50	1.3851E 07	1.50	1.5883E 02	0.	0.	1.50	3.9906E 02
2.00	2.4764E 02	2.00	1.0539E 07	2.00	1.0265E 02	0.	0.	2.00	2.9154E 02
2.50	2.3223E 02	2.50	7.6571E 06	2.50	5.9556E 01	0.	0.	2.50	2.0631E 02
3.00	2.1784E 02	3.00	5.1499E 06	3.00	2.6496E 01	0.	0.	3.00	1.3831E 02
3.50	2.0456E 02	3.50	2.9706E 06	3.50	1.1855E 00	0.	0.	3.50	8.3747E 01
4.00	1.9228E 02	4.00	1.0784E 06	3.53	1.0000E 00	0.	0.	4.00	3.9720E 01
4.50	1.8092E 02	4.32	1.0000E 01	0.	0.	0.	0.	4.50	4.0187E 00
5.00	1.7040E 02	0.	0.	0.	0.	0.	0.	4.56	1.0000E 00
5.50	1.6065E 02	0.	0.	0.	0.	0.	0.	0.	0.
6.00	1.5159E 02	0.	0.	0.	0.	0.	0.	0.	0.
6.50	1.4318E 02	0.	0.	0.	0.	0.	0.	0.	0.
7.00	1.3536E 02	0.	0.	0.	0.	0.	0.	0.	0.
7.50	1.2808E 02	0.	0.	0.	0.	0.	0.	0.	0.
8.00	1.2129E 02	0.	0.	0.	0.	0.	0.	0.	0.
8.50	1.1496E 02	0.	0.	0.	0.	0.	0.	0.	0.
9.00	1.0904E 02	0.	0.	0.	0.	0.	0.	0.	0.
9.50	1.0351E 02	0.	0.	0.	0.	0.	0.	0.	0.
10.00	9.8338E 01	0.	0.	0.	0.	0.	0.	0.	0.

END OF RUN

Figure 6.--*Fourth report of the IVST computer program showing results of use of the internal rate-of-return criterion.*

LIMITATIONS OF IVST

There are several limitations which must be observed in the use of IVST:

1. The number of alternatives analyzed within a problem must be less than or equal to 20.

2. The type of series (either terminable or perpetual) must be the same for all alternatives within a problem.

3. The number of years in the investment series for any alternative must be equal to or less than 140.

4. The length of period to which periodic annual costs or returns apply must be identical for all alternatives within a given problem. However, the number of periods may vary from one alternative to another. The number of years in each alternative (i.e., the investment series length in years) is therefore equal to the product of number of periods and period length.

5. The range and increment in interest rate must be identical for all alternatives within a given problem.

6. The beginning interest rate must be greater than -100 percent.

7. The ending interest rate must be less than 85 percent if the investment series length for any alternative in the problem is 140 years. Higher interest rates may be analyzed if the maximum investment series length decreases. Users should consult with computing center personnel regarding the limits on the exponential function subroutine being used, as this is the factor that limits the range of interest rates which may be analyzed.

8. The interest rate range and increment selected by the user must not result in more than 200 interest rates being generated. However, more than 200 interest rates may be generated during the bisection procedure, which is not under the user's control but is automatically controlled by the IROR subroutine.

9. An attempt to analyze a zero interest rate for a perpetual series will result in the program skipping that rate and passing on to the next interest rate within the range selected by the user. No program stop or computational error will result.

OPERATION OF IVST

Input card formats, program flow charts, and a listing of the IVST source program are included in the Appendix. IVST is coded in FORTRAN IV and is operable on either the IBM 7040 or the IBM 360/50 (both time-sharing and nontime-sharing modes) computing systems. Slight modification may be necessary before IVST can be used with other systems. A total of 31,988 words of core storage are required on the IBM 7040 computer for this program. Use of IVST on computers with smaller memory capacities will require modification of the program. The sample problem shown in this paper required 1 minute and 4 seconds of execution time on the IBM 7040.

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APPENDIX

Preparation of IVST Input Cards

There are nine types of input cards required by the IVST program. The format of these input cards is indicated in table 1. Card columns for which no punch is indicated should be left blank. All data except alphanumeric must be right-justified (i.e., the units position must be at the extreme right of the field). It should be pointed out that input card types 1-6 and 9 contain identification and control data, whereas input card types 7 (periodic annual costs) and 8 (periodic annual returns) are sets of data applicable to independent alternatives. All costs are read for a given alternative. Then all returns are read for that same alternative. This sequence (i.e., all costs and then all returns for each alternative) is repeated until all alternatives have been read before the next input card type is read. The last card contains the end-of-problem indicator (MEND).

BCA Optional Output

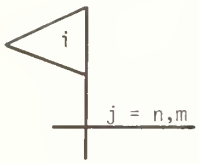
The discounted returns and discounted costs at each interest rate may be printed if the user desires. The only modification required in the BCA subroutine to provide for this output is to reproduce BCA program cards BCA 0370 and BCA 0375 (see listing of the BCA subroutine) deleting the "C" in the first column.

Table 1.-- IVST Program Input Format

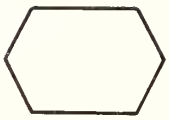
Input card type	Program code	Item	Form	Card columns
1	STO(I)	Alphanumeric study identification.	A.....A	1-72
2	BRATE	Beginning interest rate, decimal.	X.XX	7-10
2	FRATE	Final interest rate, decimal.	X.XX	17-20
2	DELTA	Interest rate increment, decimal.	X.XX	27-30
2	LX	Number of alternatives in problem.	XX	34-35
2	INIT	Indicator of an initial cost or return; = 0, if there is an initial cost or return, = 1, if not.	X	40
3	LI(I,L)	Alphanumeric identification of alternative L. A second card is needed to handle over 10 alternatives.	AAAAAAAA	1-8, 9-16, ..., 73-80
4	NO	Problem number.	XXXX	1-4
4	NZ	Type of calculation; = 01, if series is perpetual, = 02, if series is terminable.	XX	7-8
4	IC	Investment criterion; = 01, internal rate of return, = 02, benefit/cost and present net worth, = 03, all three criteria.	XX	11-12
4	IP	Length of period, years.	XX	15-16
4	KCXX	Maximum number of years in the investment series of any alternative. If initial costs and returns are read, present year should be included in KCXX.	XXX	18-20
5	KCX(L)	Number of years in the investment series of each alternative L. If initial costs and returns are read, present year should be included in KCX(L).	XXX	1-3, 4-6, ..., 58-60
6	A(I)	Alphanumeric problem identification.	A.....A	1-72
7	COST(L,KC)	Periodic annual cost of alternative L, for period KC, dollars. A second card is needed to handle 9-16 alternatives. A third card is needed to handle 17-20 alternatives.	XXXXXXXXXX	1-10, 11-20, ..., 71-80
8	REV(L,KC)	Periodic annual return of alternative L for period KC, dollars. A second card is needed to handle 9-16 alternatives. A third card is needed to handle 17-20 alternatives.	XXXXXXXXXX	1-10, 11-20, ..., 71-80
9	MEND	Terminal card code; = 98, to do another problem. = 99, end-of-run.	XX	2-3

FLOW CHART FOR MAIN ROUTINE IVST

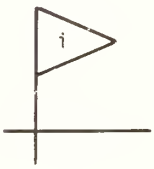
LEGEND FOR FLOW CHARTS



START OF DO LOOP i
INDEX j, LIMITS n,m.



SUBROUTINE
CALL OR RETURN

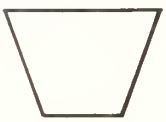


TERMINUS OF LOOP i

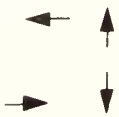
PROGRAM
BEGINNING AND END

COMPUTATION
OR PROCESSING

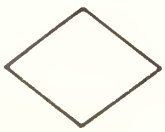
AN ENTRY FROM, OR EXIT
TO, ANOTHER PART OF
THE PROGRAM FLOWCHART



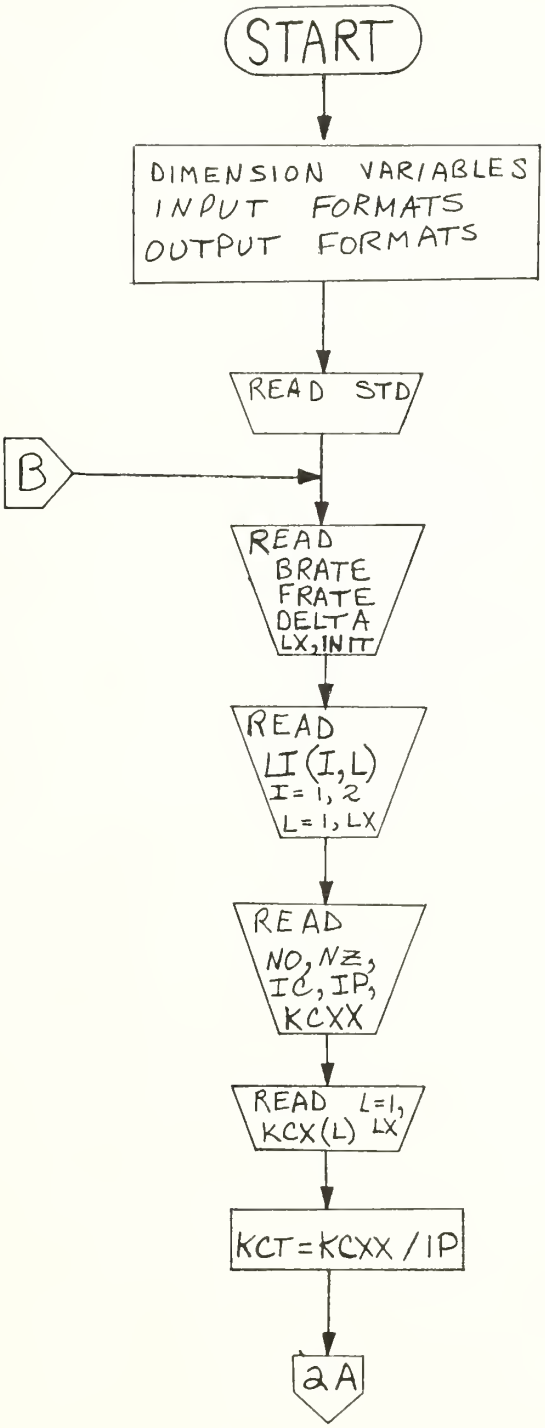
INPUT OR OUTPUT

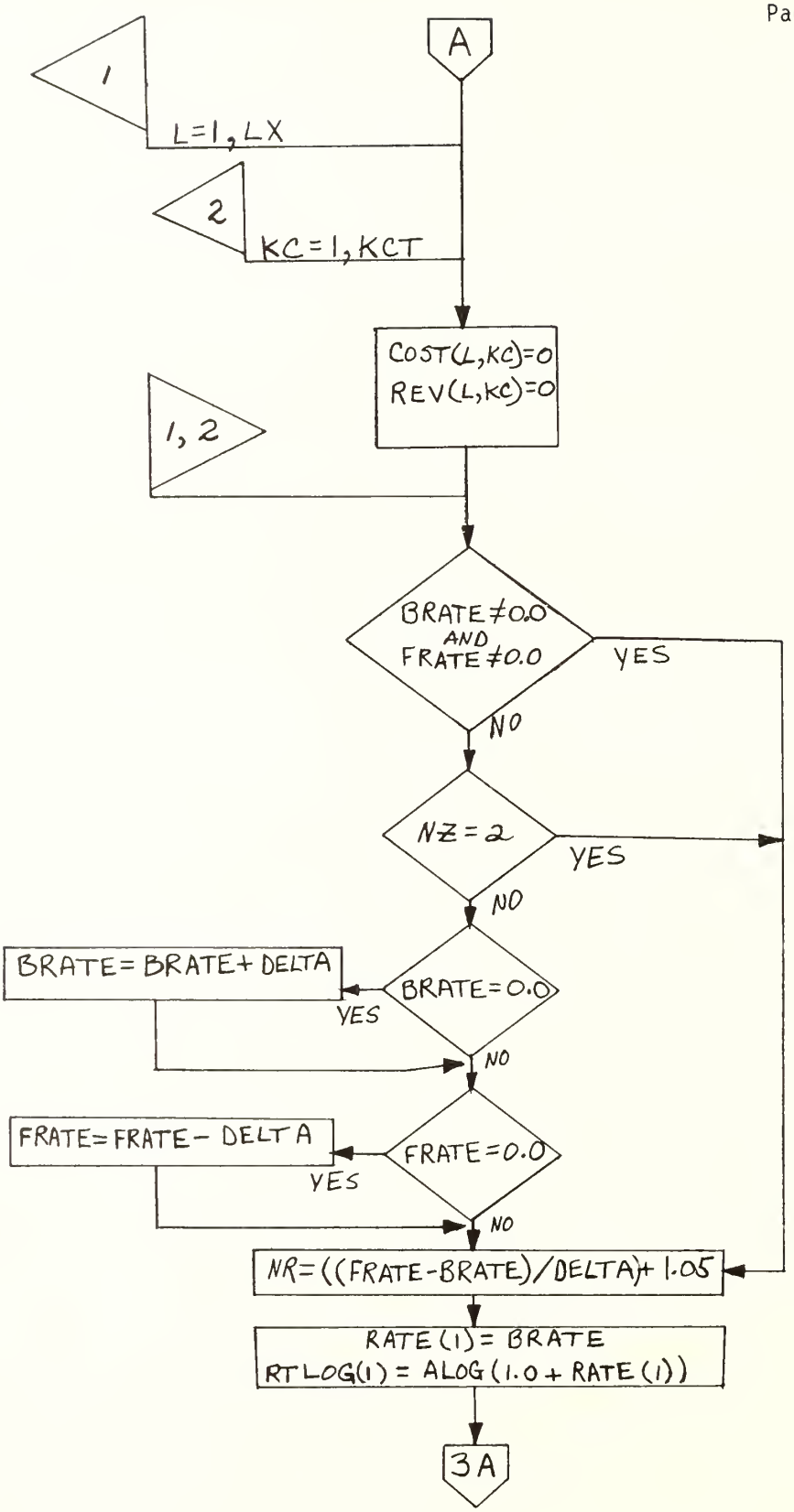


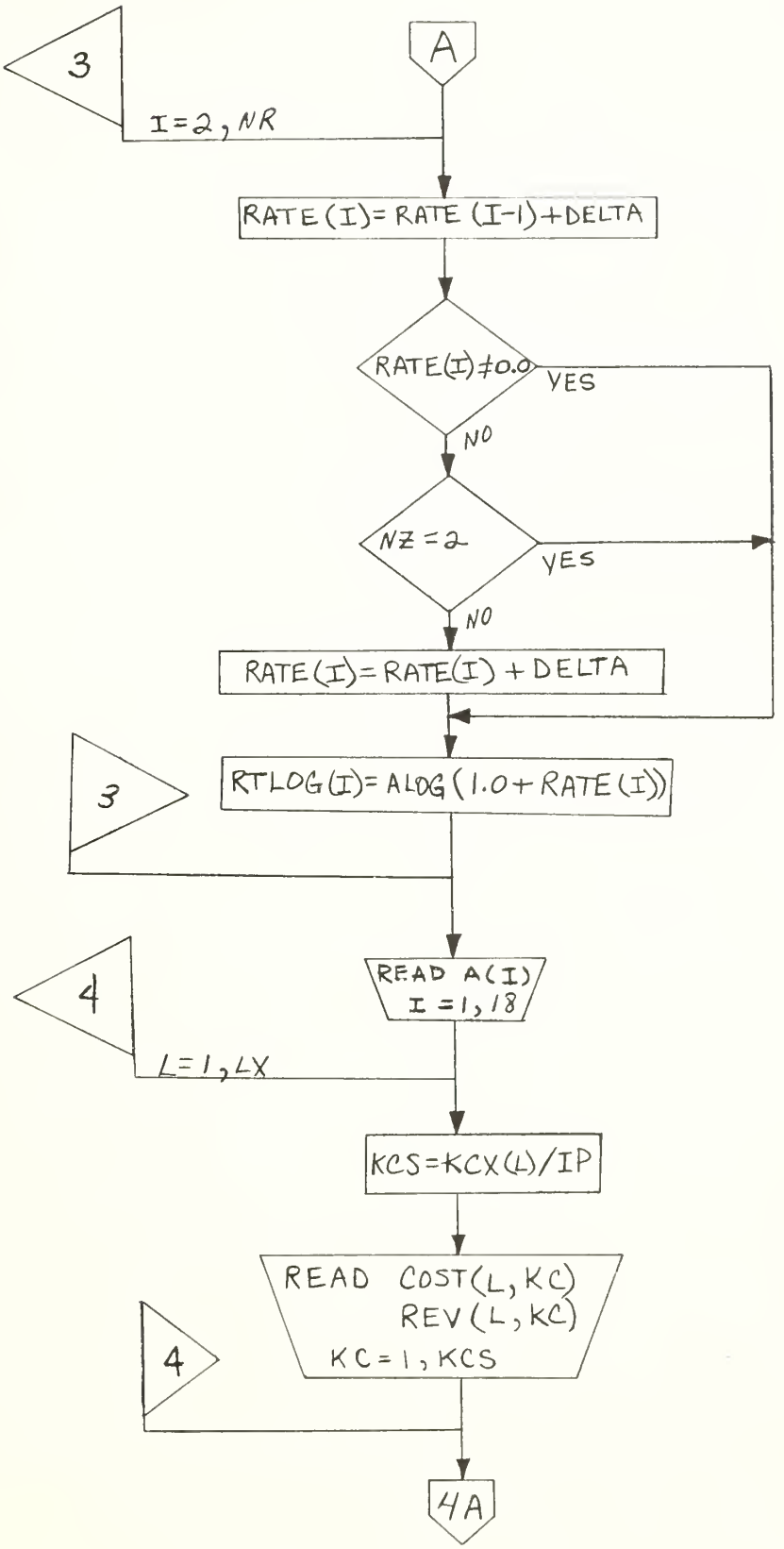
DIRECTION OF FLOW

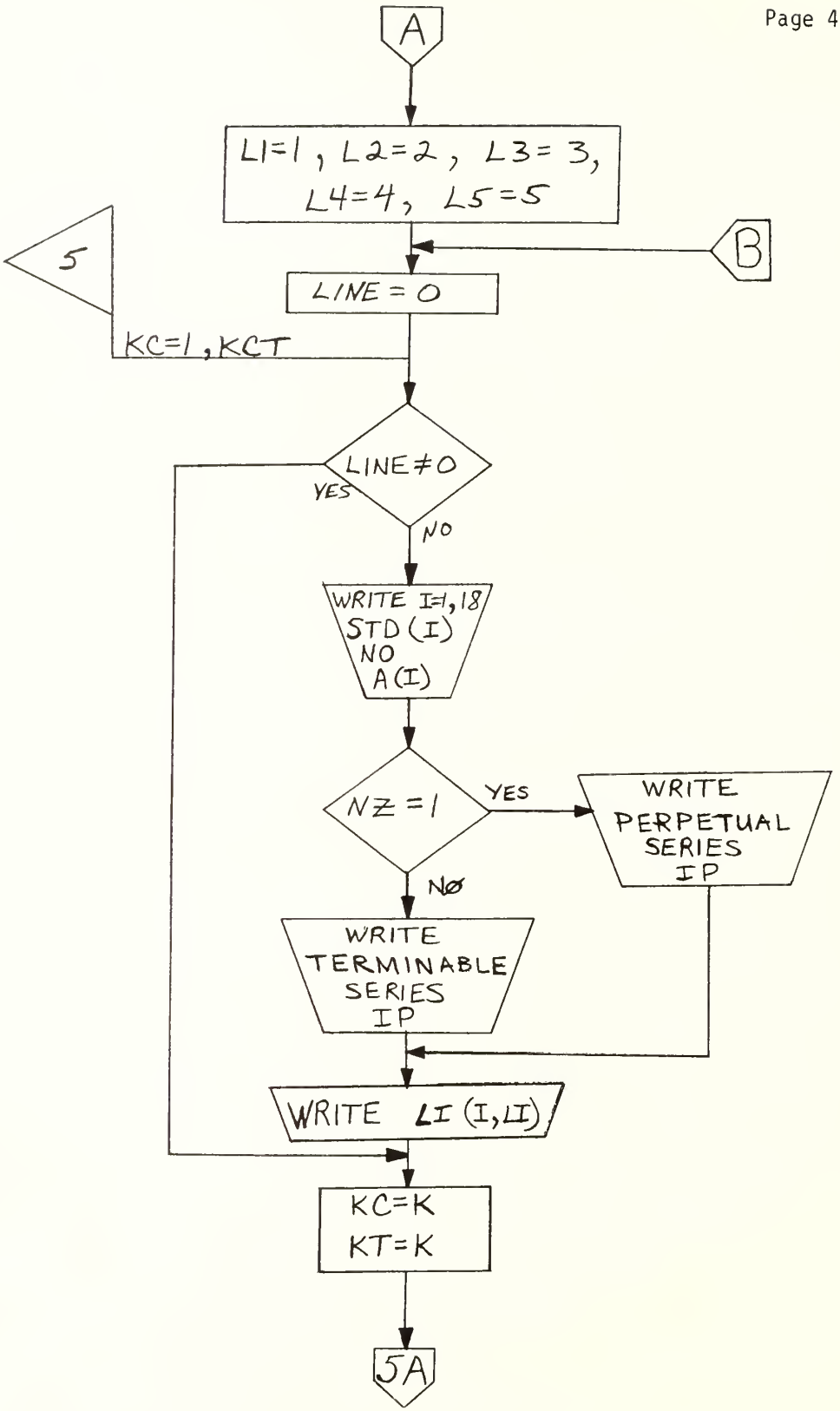


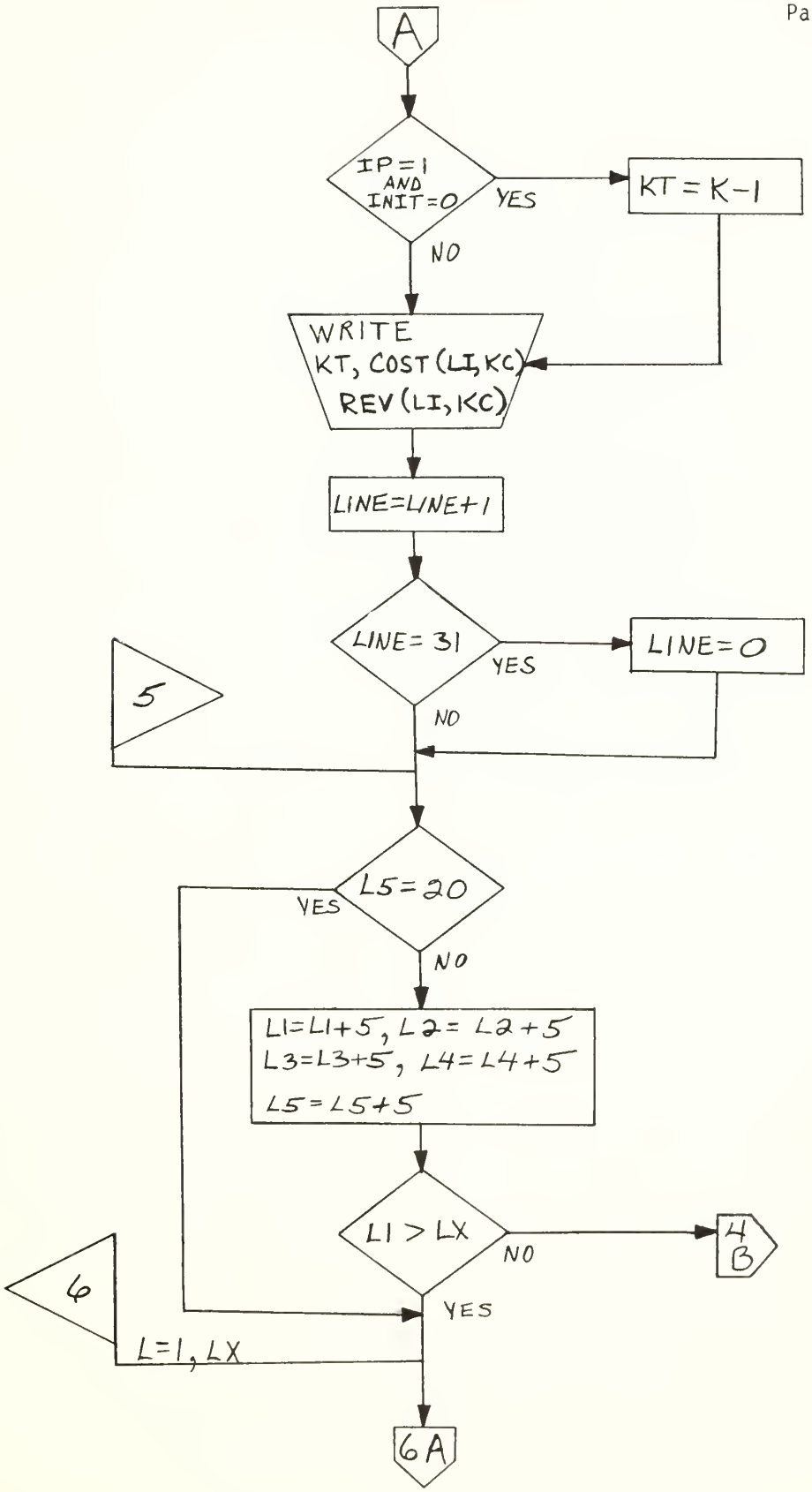
DECISION

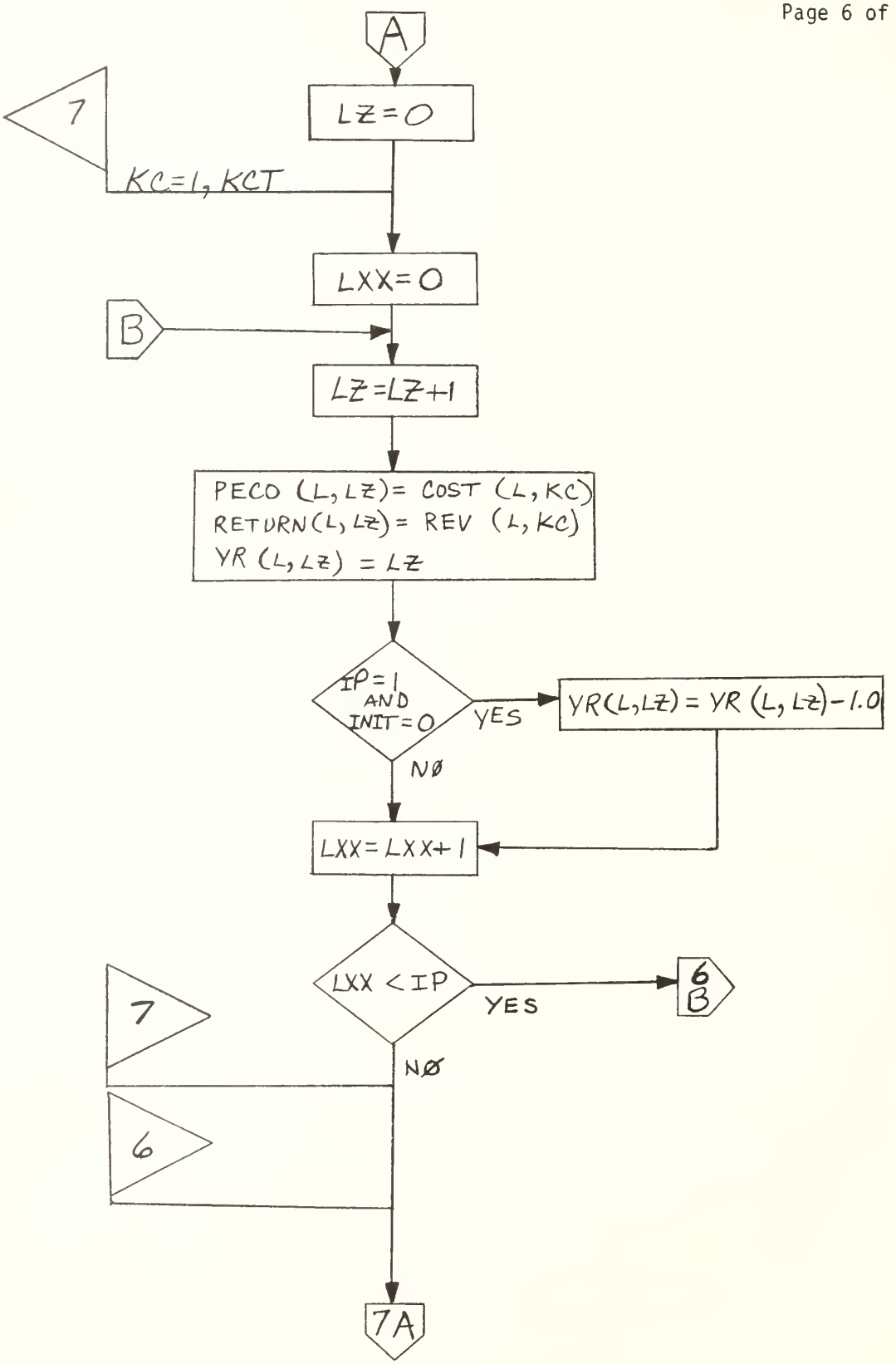

START
DIMENSION VARIABLES
INPUT FORMATS
OUTPUT FORMATS
READ STD
B
READ
BRATE
FRATE
DELTA
LX, INIT
READ
LI(I,L)
I=1,2
L=1,LX
READ
NO, NZ,
IC, IP,
KCXX
READ L=1,
KCX(L) LX
KCT=KCXX/IP
2A

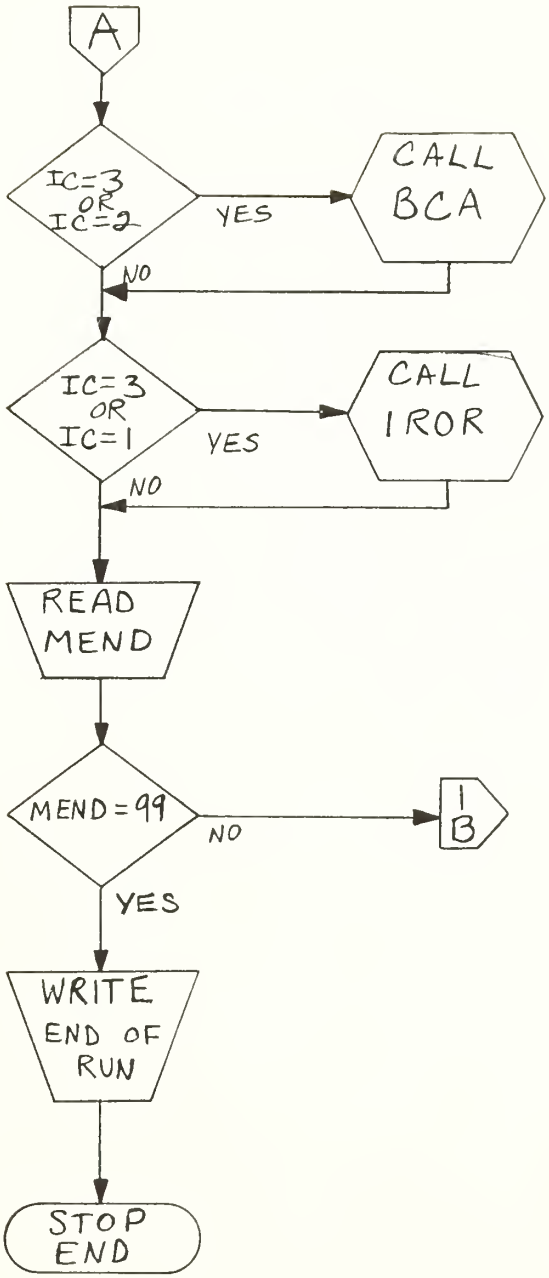

A
1
L=1, LX
2
KC=1, KCT
COST(L,KC)=0
REV(L,KC)=0
1, 2
BRATE≠0.0 AND FRATE≠0.0
YES
NO
NZ=2
YES
NO
BRATE=BRATE+DELTA
BRATE=0.0
YES
NO
FRATE=FRATE-DELTA
FRATE=0.0
YES
NO
NR=((FRATE-BRATE)/DELTA)+1.05
RATE(I)=BRATE
RTLOG(I)=ALOG(1.0+RATE(I))
3A


3
I=2, NR
A
RATE(I)= RATE(I-1)+DELTA
RATE(I)≠0.0
YES
NO
NZ=2
YES
NO
RATE(I)= RATE(I) + DELTA
3
RTLOG(I)= ALOG(1.0+RATE(I))
4
L=1, LX
READ A(I)
I=1, 18
KCS=KCX(L)/IP
READ COST(L, KC)
REV(L, KC)
KC=1, KCS
4
4A

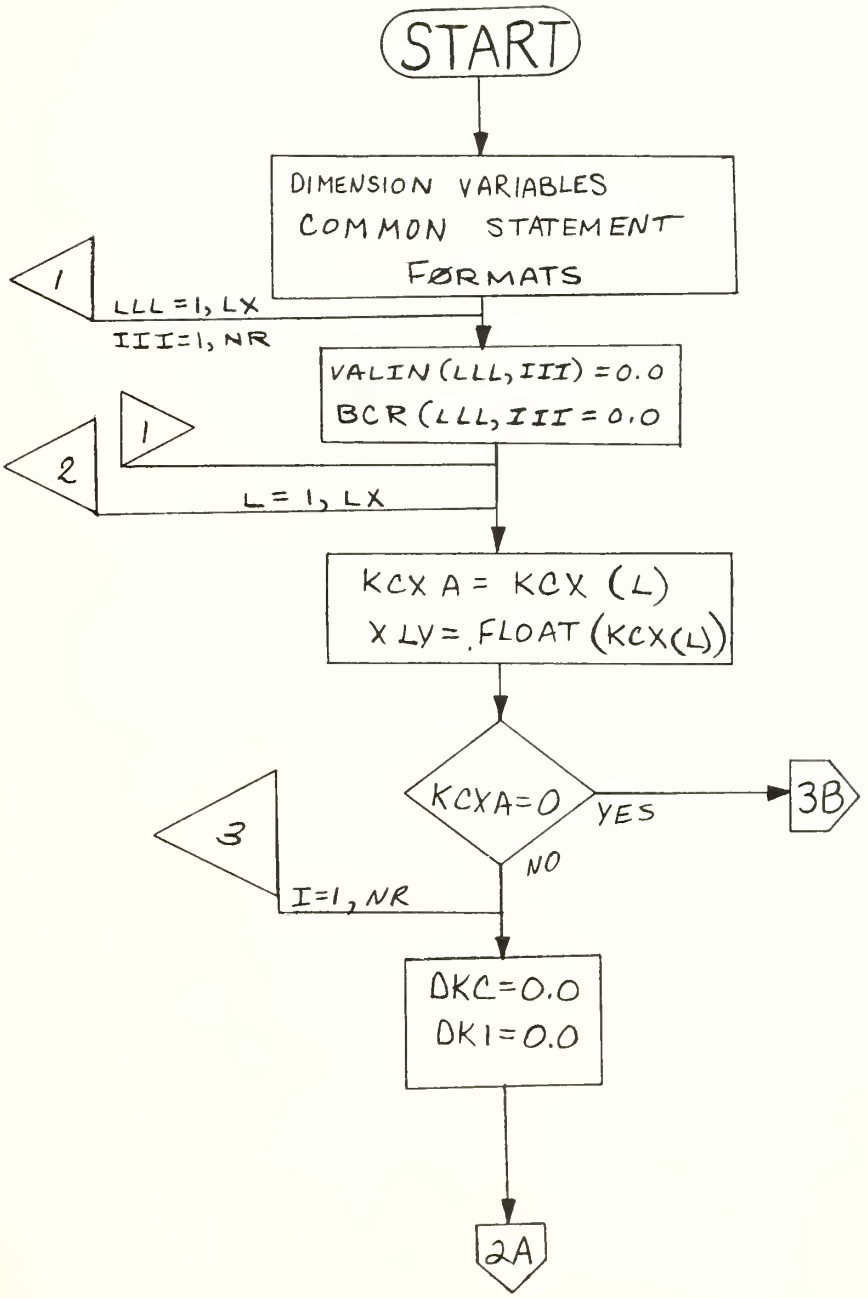

A
L1=1, L2=2, L3=3,
L4=4, L5=5
B
5
LINE = 0
KC=1, KCT
LINE≠0
YES
NO
WRITE I=1,18
STD(I)
NO
A(I)
NZ=1
YES
WRITE
PERPETUAL
SERIES
IP
NØ
WRITE
TERMINABLE
SERIES
IP
WRITE LI(I,LI)
KC=K
KT=K
5A

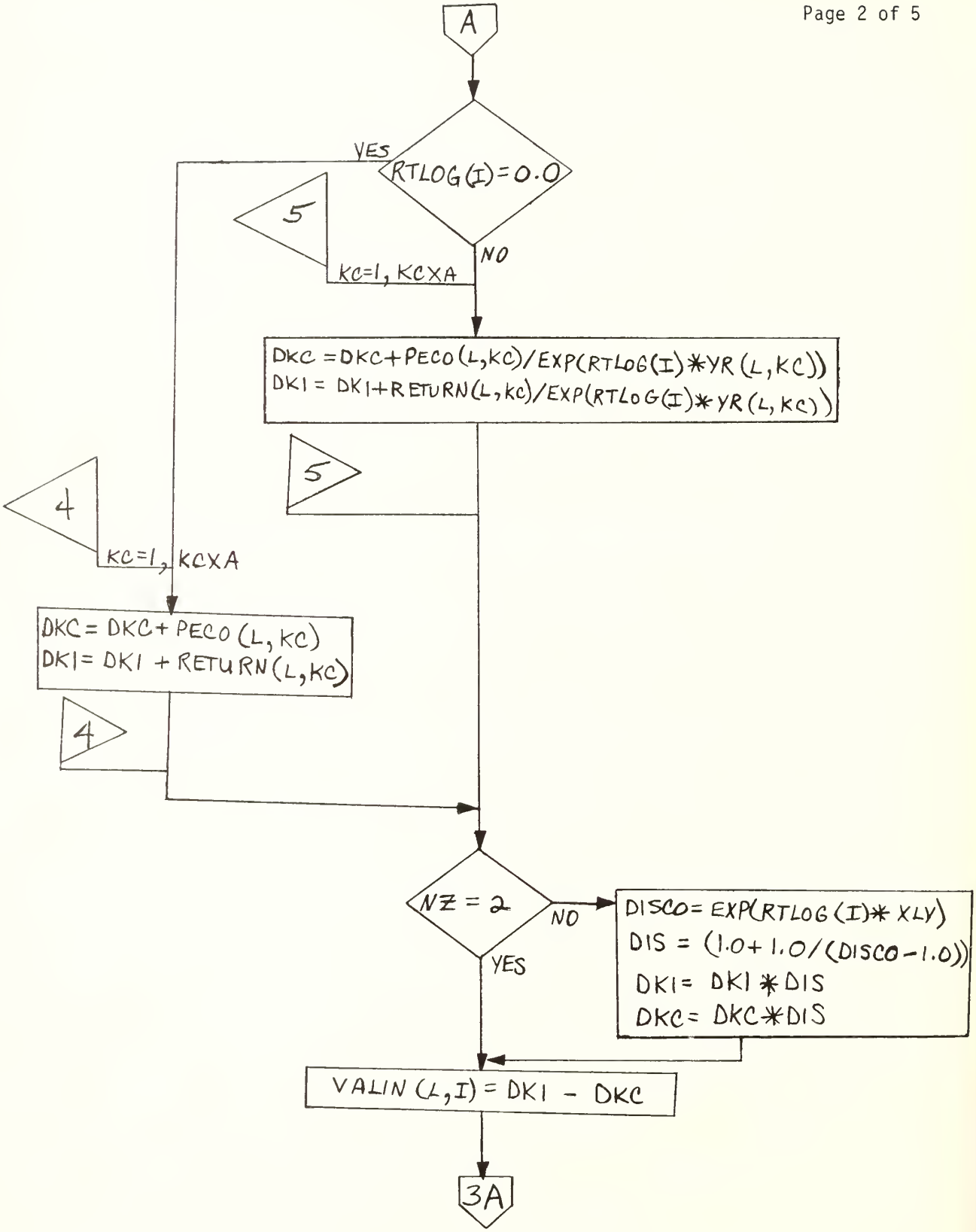

A
IP=1 AND INIT=0
YES
KT = K-1
NO
WRITE KT, COST(LI,KC) REV(LI,KC)
LINE=LINE+1
LINE=31
YES
LINE=0
NO
5
L5=20
YES
NO
LI=LI+5, L2=L2+5
L3=L3+5, L4=L4+5
L5=L5+5
LI > LX
NO
4 B
YES
6
L=1, LX
6A

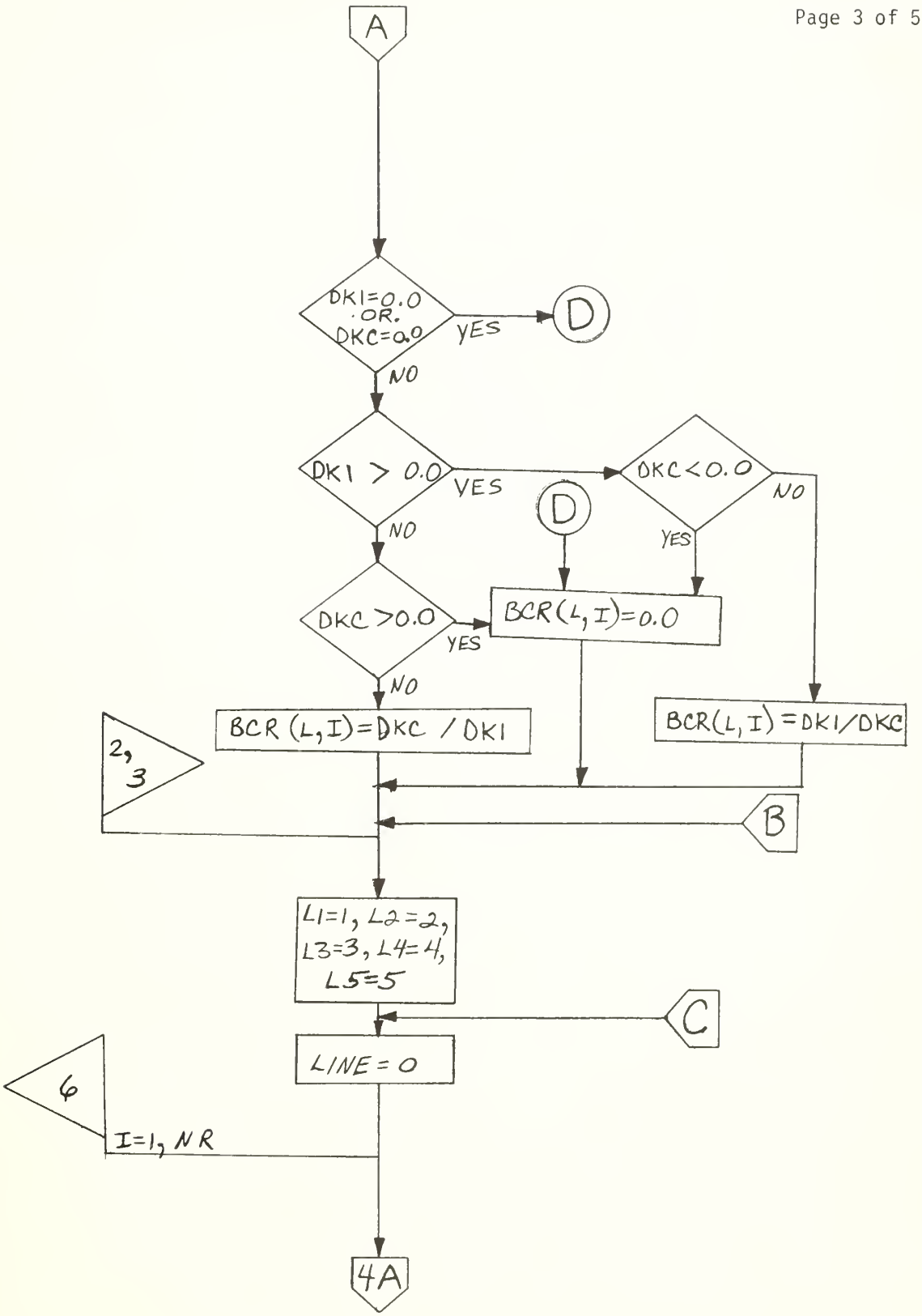

A
LZ=0
7
KC=1, KCT
LXX=0
B
LZ=LZ+1
PECO (L, LZ)= COST (L, KC)
RETURN(L, LZ)= REV (L, KC)
YR (L, LZ) = LZ
IP=1 AND INIT=0
YES
YR(L,LZ) = YR (L, LZ)-1.0
NØ
LXX=LXX+1
LXX < IP
YES
6 B
7
NØ
6
7A

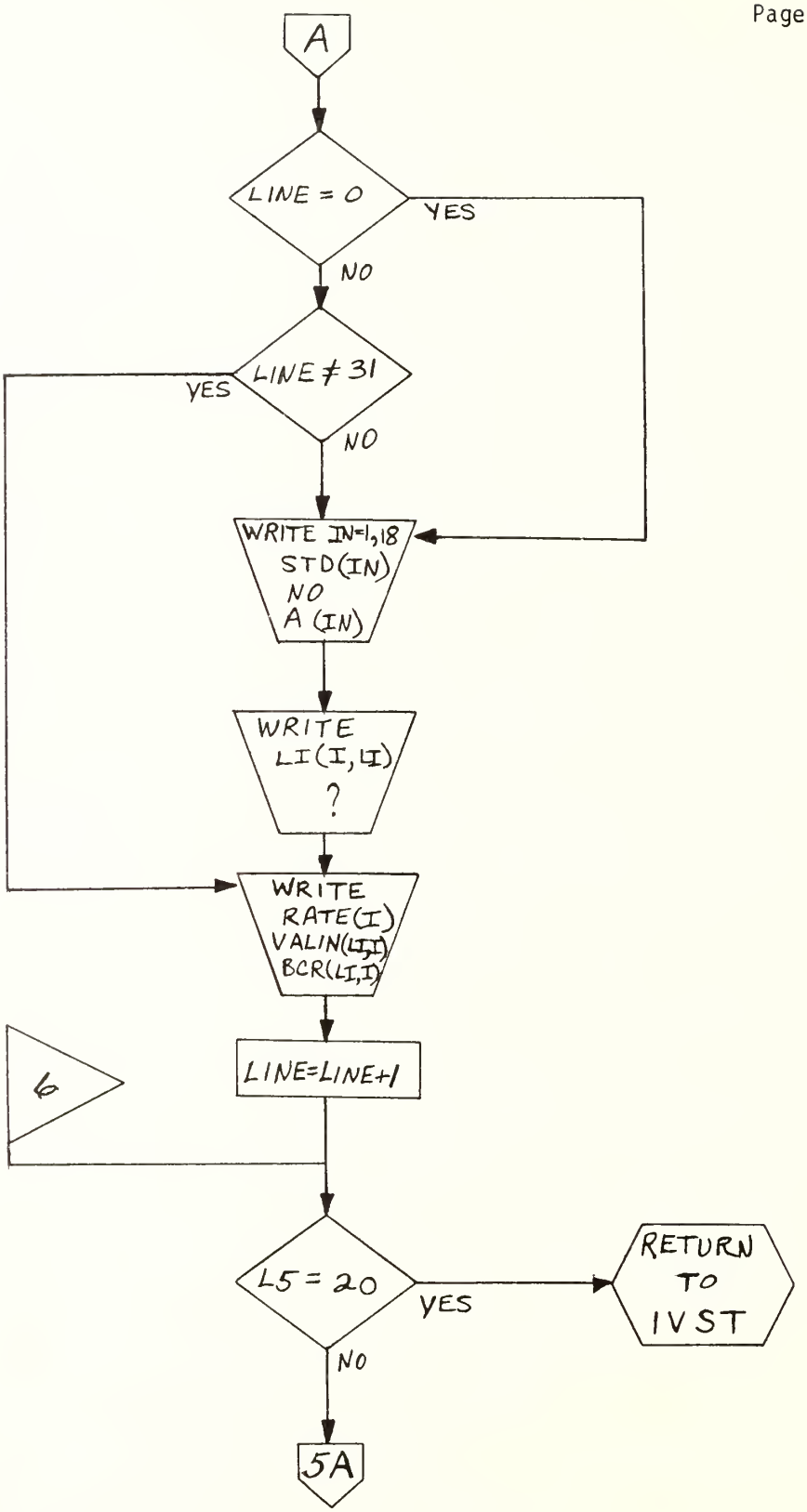

A
IC=3 OR IC=2
YES
CALL BCA
NO
IC=3 OR IC=1
YES
CALL IROR
NO
READ MEND
MEND=99
NO
1 B
YES
WRITE END OF RUN
STOP END

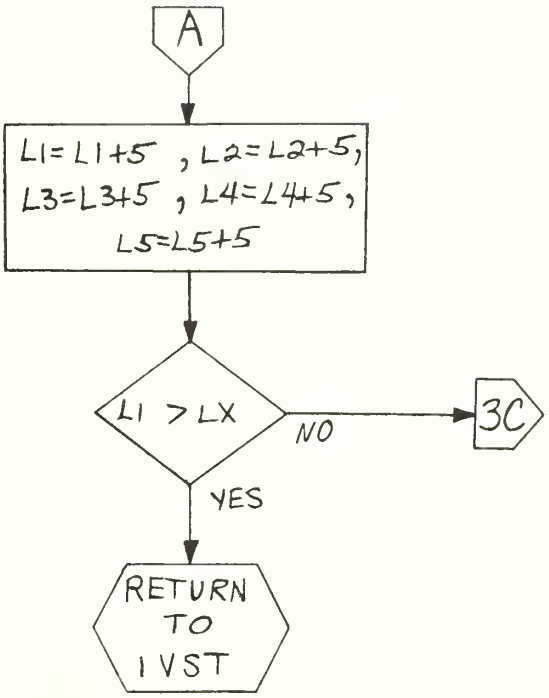
FLOW CHART FOR SUBROUTINE BCA


START
DIMENSION VARIABLES
COMMON STATEMENT
FORMATS
1
LLL=1, LX
III=1, NR
VALIN(LLL, III)=0.0
BCR(LLL, III=0.0
1
2
L=1, LX
KCX A = KCX (L)
X LY = FLOAT (KCX(L))
KCXA=0
YES
3B
NO
3
I=1, NR
DKC=0.0
DK1=0.0
2A

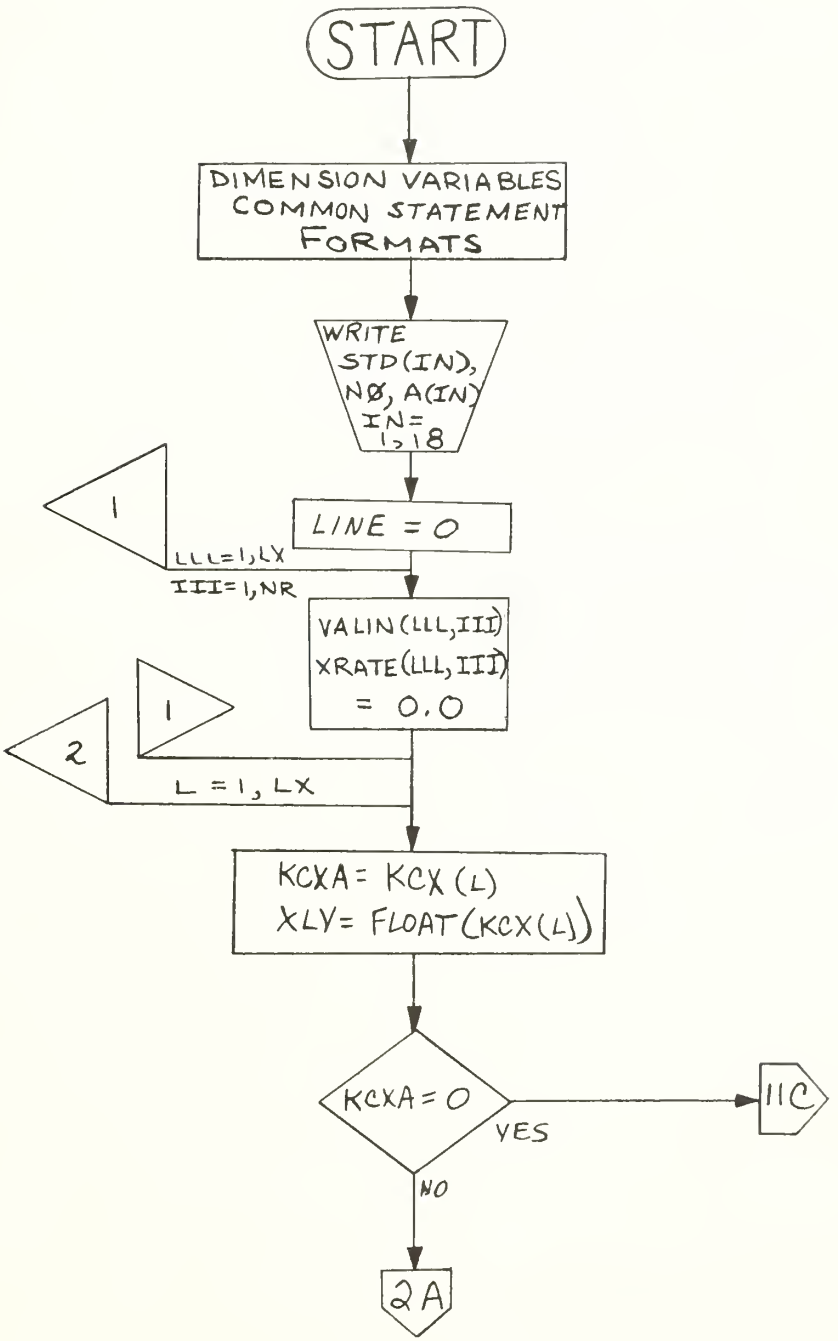

A
RTLOG(I)=0.0
YES
NO
5
KC=1, KCXA
DKC =DKC+PECO(L,KC)/EXP(RTLOG(I)*YR(L,KC))
DK1 = DK1+RETURN(L,KC)/EXP(RTLOG(I)*YR(L,KC))
5
4
KC=1, KCXA
DKC = DKC+ PECO (L, KC)
DK1= DK1 + RETURN(L,KC)
4
NZ = 2
NO
YES
DISCO= EXP(RTLOG (I)* XLY)
DIS = (1.0+1.0/(DISCO-1.0))
DK1= DK1 * DIS
DKC= DKC*DIS
VALIN (L,I) = DK1 - DKC
3A

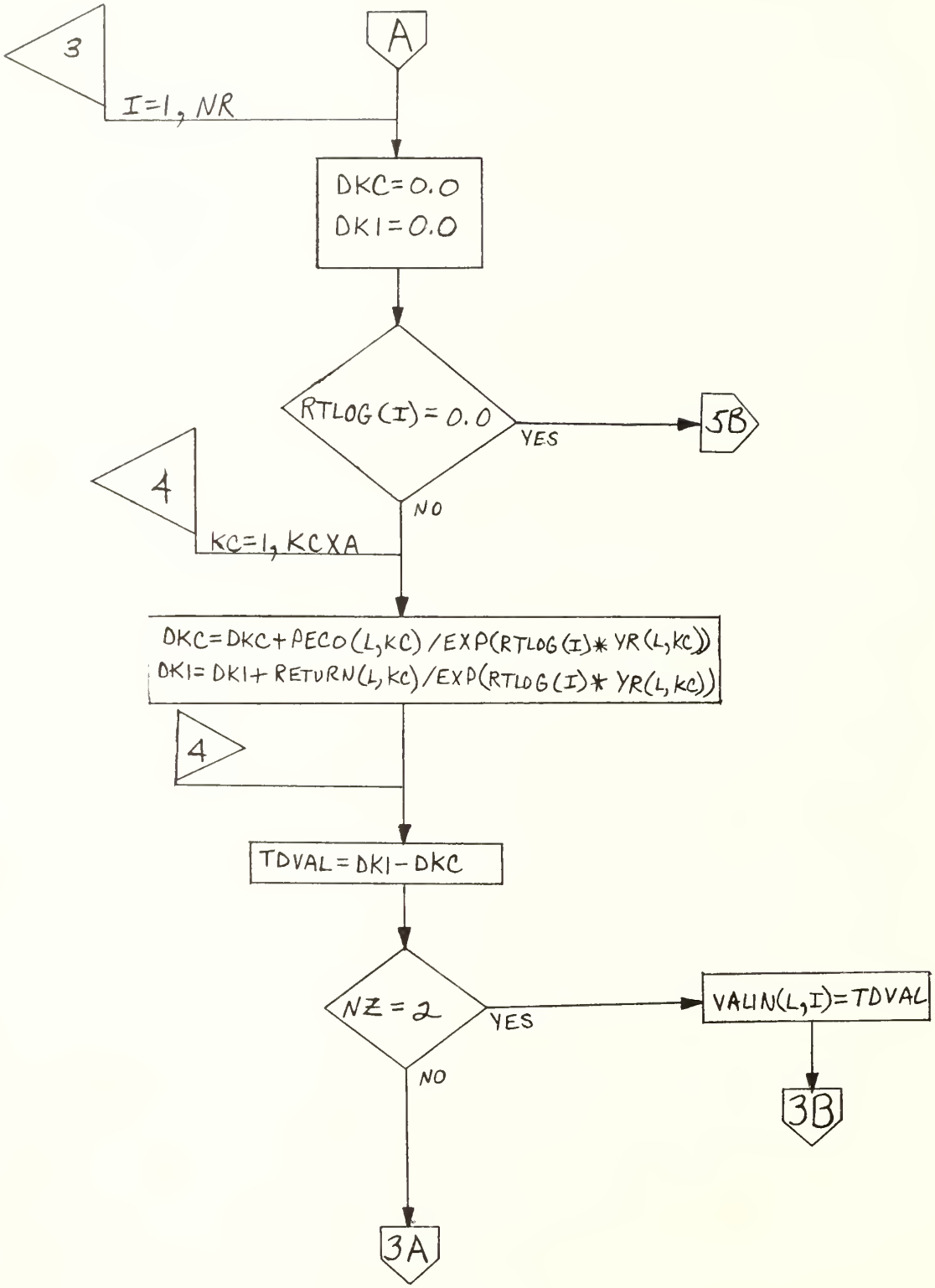

A
DK1=0.0 .OR. DKC=0.0
YES
D
NO
DK1 > 0.0
YES
DKC<0.0
NO
YES
D
NO
DKC >0.0
YES
BCR(L,I)=0.0
NO
BCR (L,I)=DKC / DK1
BCR(L,I) =DK1/DKC
2, 3
B
L1=1, L2=2, L3=3, L4=4, L5=5
C
LINE = 0
6
I=1, NR
4A

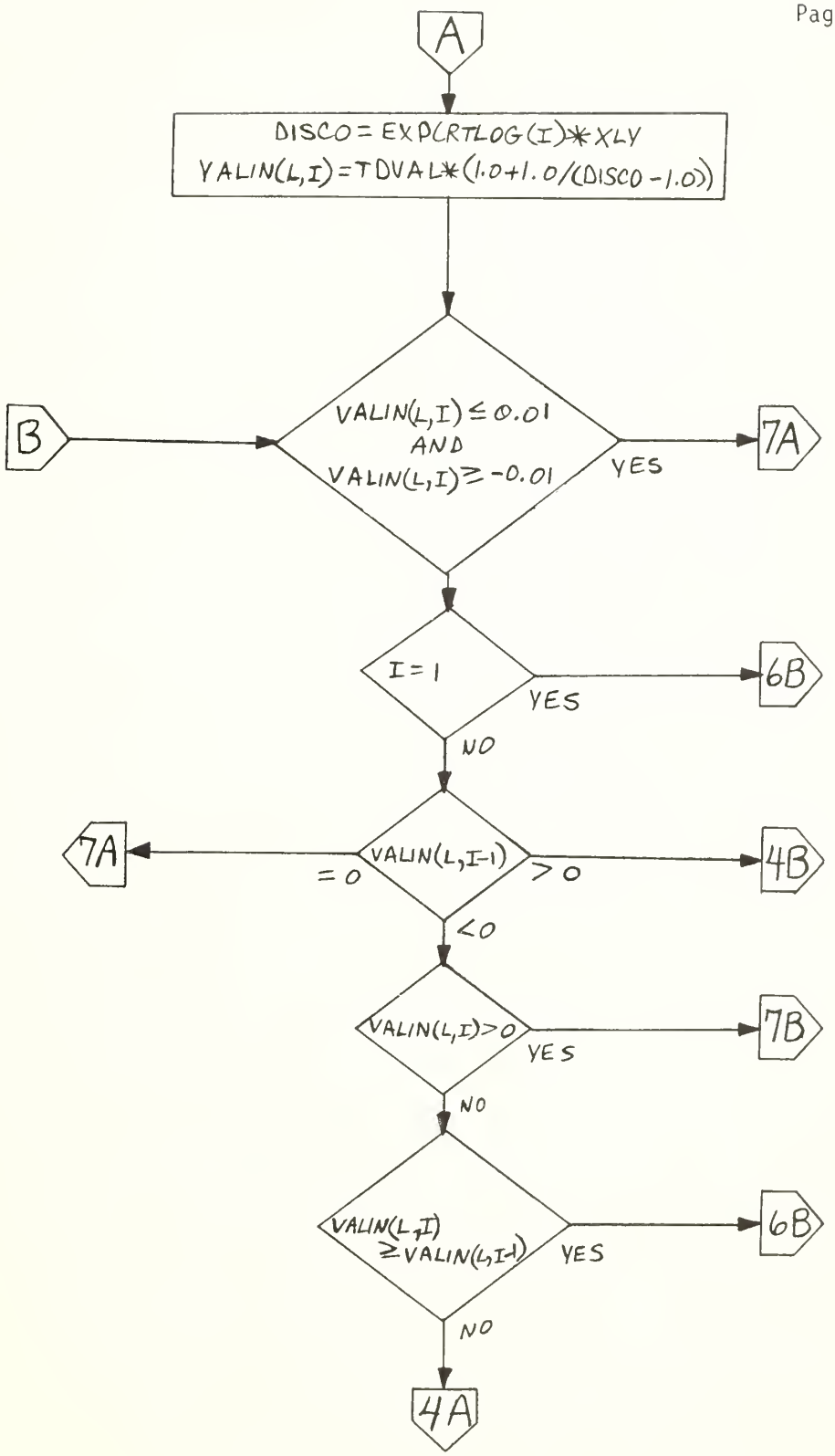

A
LINE = 0
YES
NO
LINE ≠ 31
YES
NO
WRITE IN=1,18
STD(IN)
NO
A (IN)
WRITE
LI(I,LI)
?
WRITE
RATE(I)
VALIN(LI,I)
BCR(LI,I)
6
LINE=LINE+1
L5 = 20
YES
RETURN
TO
IVST
NO
5A

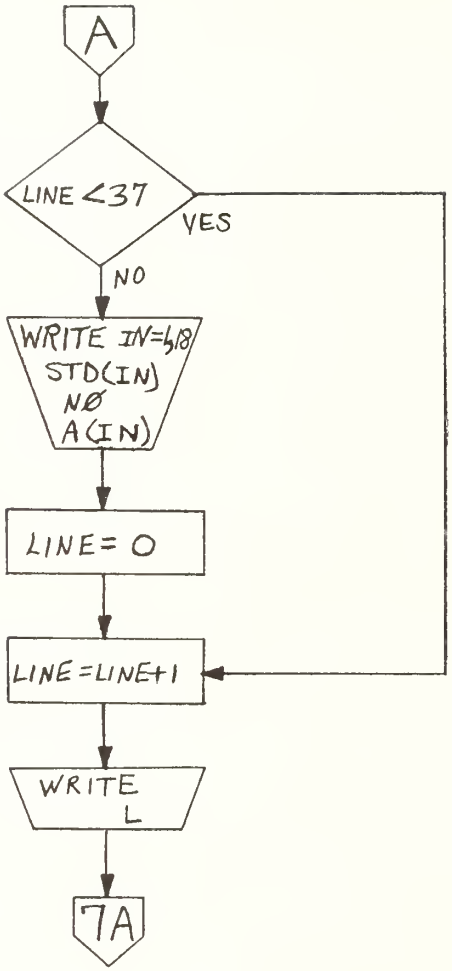

A
L1=L1+5 , L2=L2+5,
L3=L3+5 , L4=L4+5,
L5=L5+5
L1 > LX
NO
3C
YES
RETURN
TO
IVST

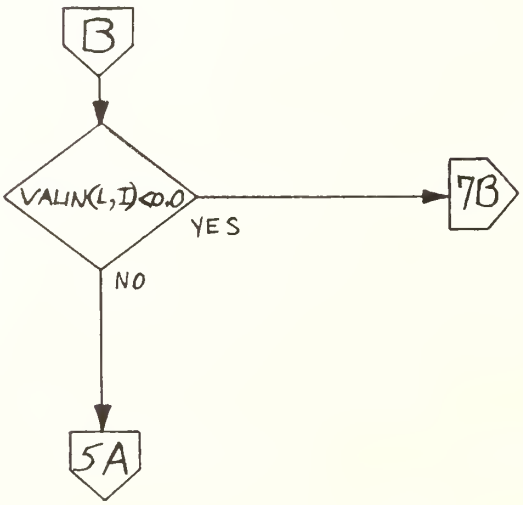
FLOW CHART FOR SUBROUTINE IROR

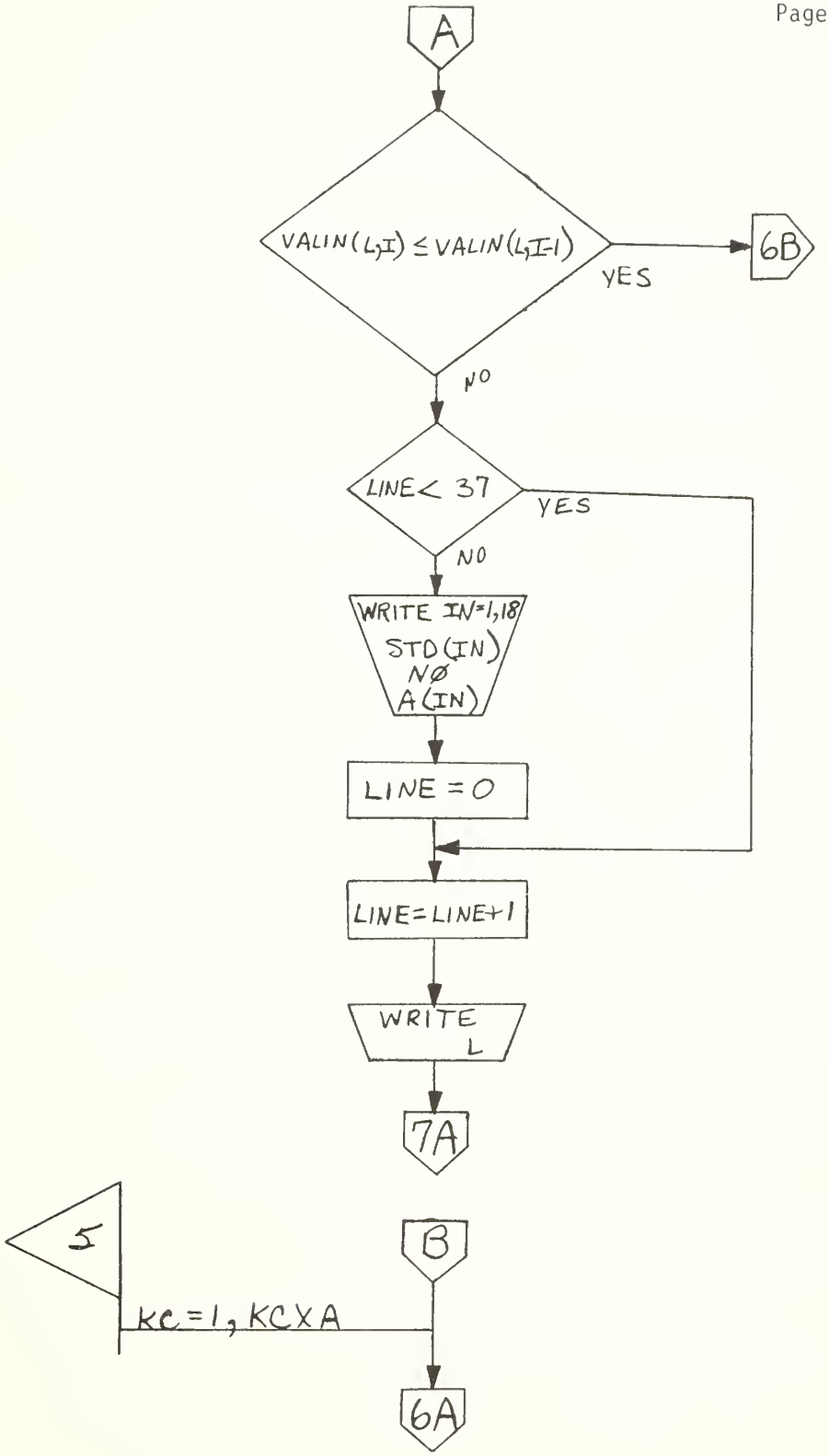

START
DIMENSION VARIABLES
COMMON STATEMENT
FORMATS
WRITE
STD(IN),
NØ, A(IN)
IN=
1,18
1
LLL=1,LX
III=1,NR
LINE = 0
VALIN(LLL,III)
XRATE(LLL,III)
= 0.0
1
2
L = 1, LX
KCXA = KCX(L)
XLY = FLOAT(KCX(L))
KCXA = 0
YES
11C
NO
2A

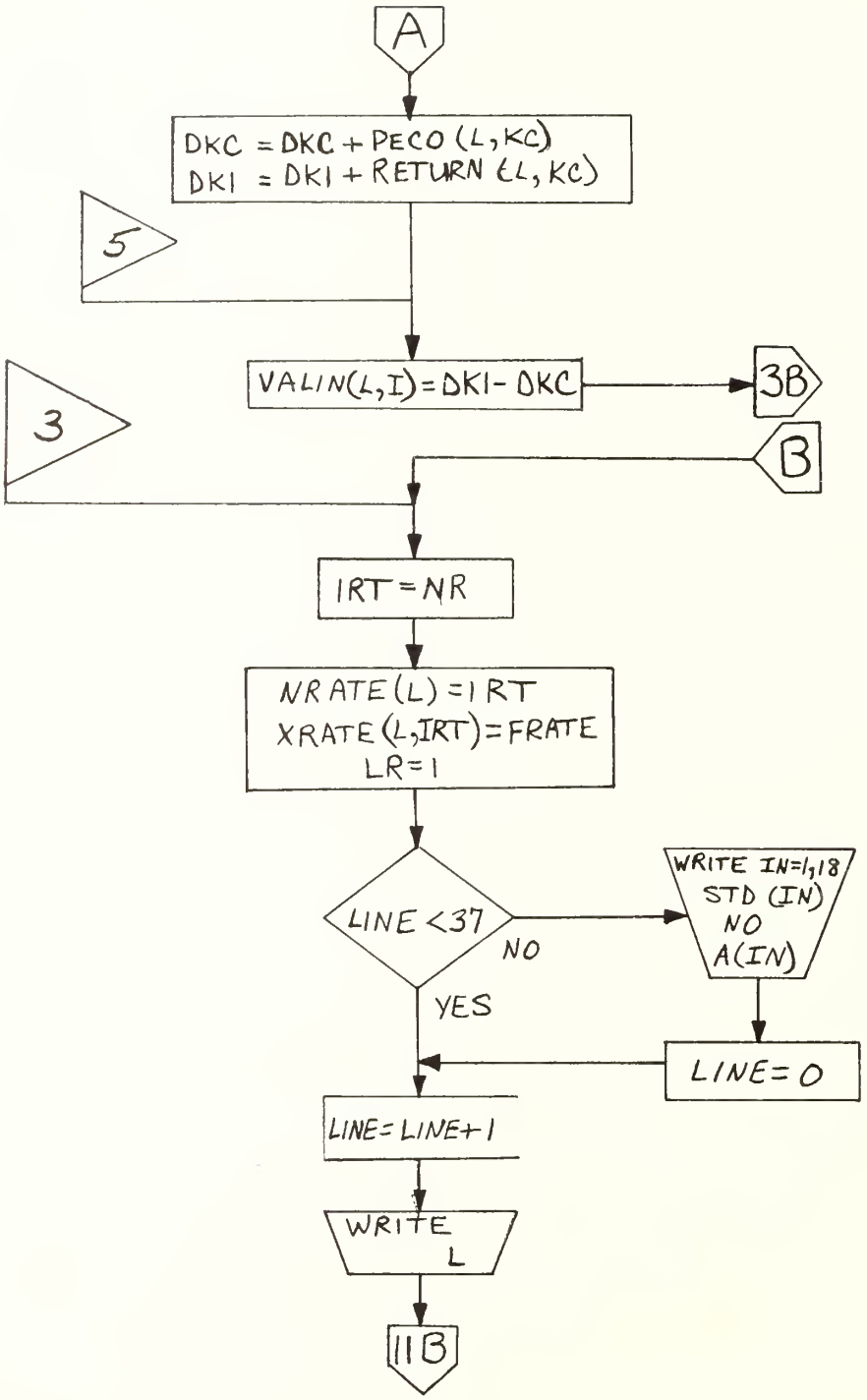

3
I=1, NR
A
DKC=0.0
DKI=0.0
RTLOG(I) = 0.0
YES
5B
NO
4
KC=1, KCXA
DKC=DKC+PECO(L,KC) /EXP(RTLOG(I)* YR(L,KC))
DKI= DKI+ RETURN(L,KC)/EXP(RTLOG(I)* YR(L,KC))
4
TDVAL = DKI - DKC
NZ = 2
YES
VALIN(L,I)=TDVAL
3B
NO
3A

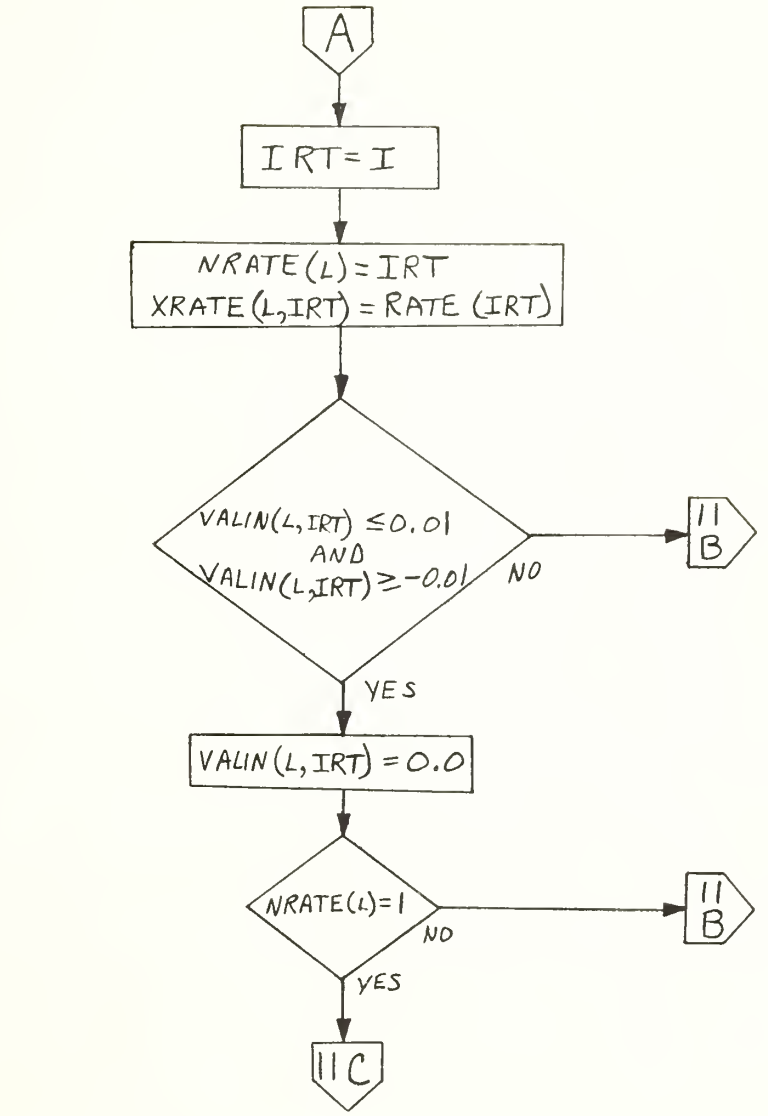

A
DISCO = EXP(RTLOG(I)*XLY
YALIN(L,I) = TDVAL*(1.0+1.0/(DISCO-1.0))
B
VALIN(L,I) ≤ 0.01
AND
VALIN(L,I) ≥ -0.01
YES
7A
I = 1
YES
6B
NO
7A
VALIN(L,I-1)
= 0
> 0
4B
< 0
VALIN(L,I) > 0
YES
7B
NO
VALIN(L,I)
≥ VALIN(L,I-1)
YES
6B
NO
4A

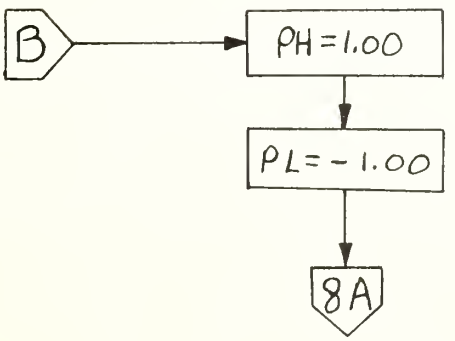

A
LINE <37
YES
NO
WRITE IN=4,18
STD(IN)
NØ
A(IN)
LINE= 0
LINE =LINE+1
WRITE
L
7A

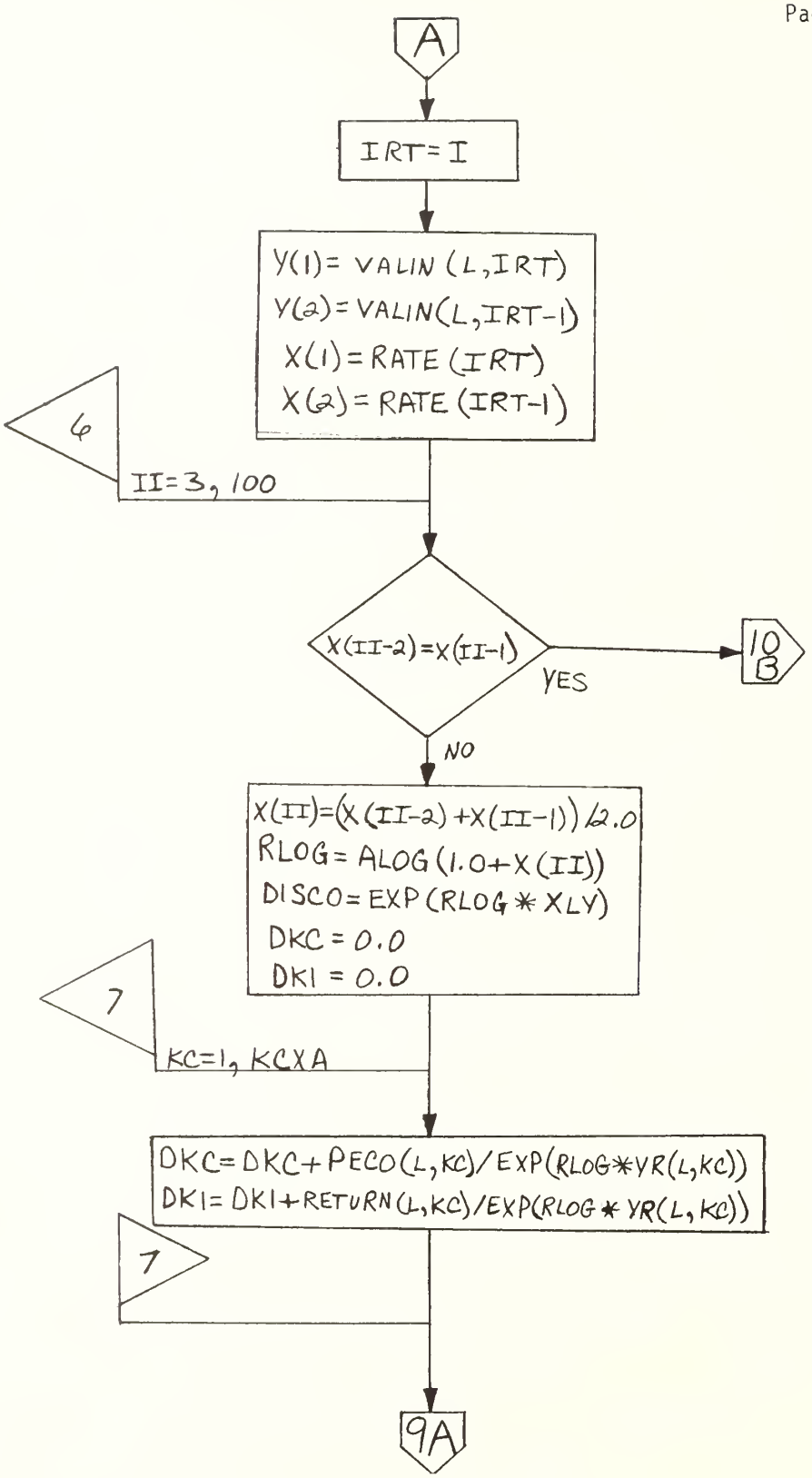

B
VALIN(L,I)<0.0
YES
7B
NO
5A

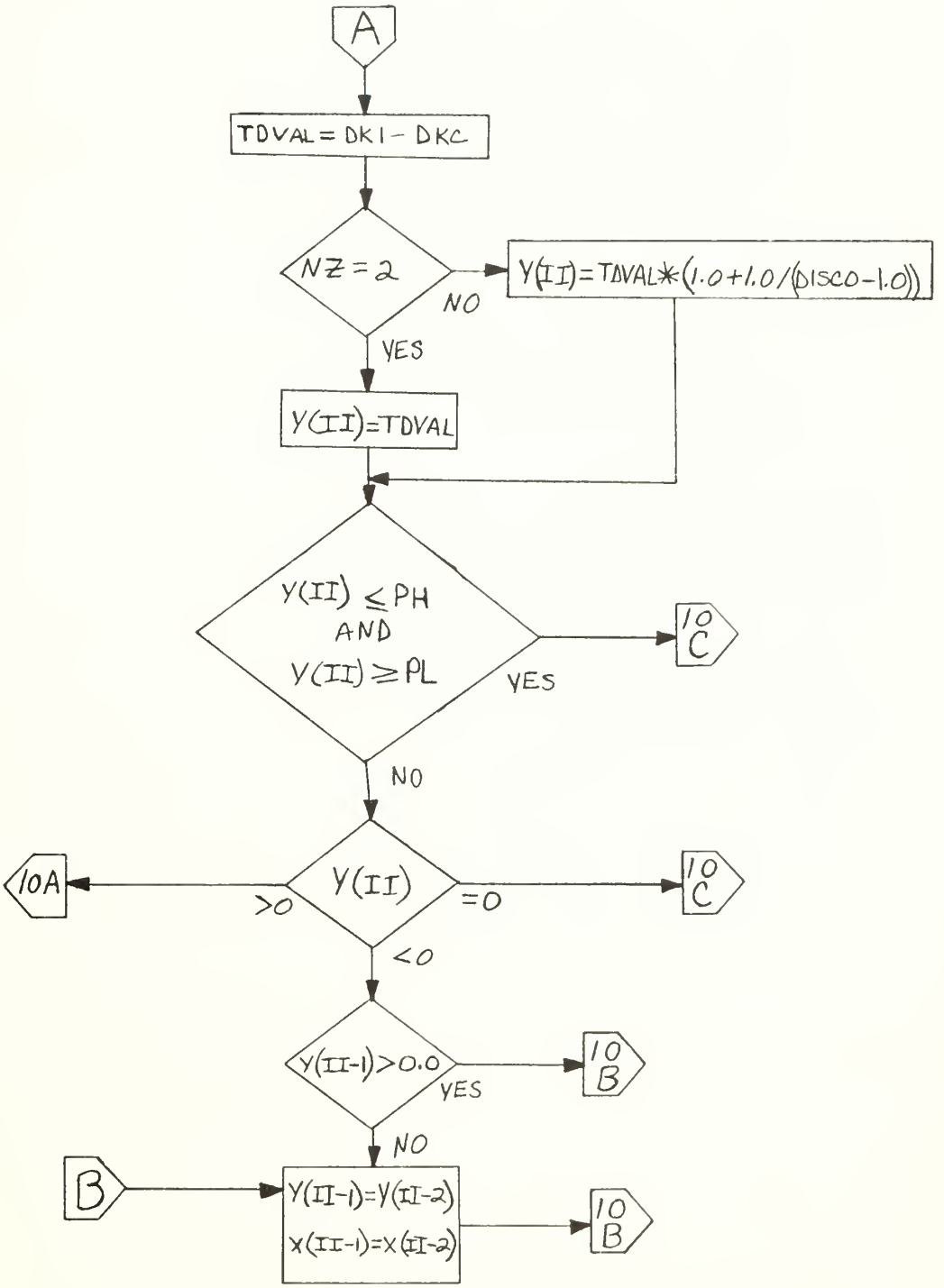

A
VALIN(L,I) ≤ VALIN(L,I-1)
YES
6B
NO
LINE< 37
YES
NO
WRITE IN=1,18
STD(IN)
NØ
A(IN)
LINE = 0
LINE=LINE+1
WRITE
L
7A
5
B
KC=1, KCXA
6A

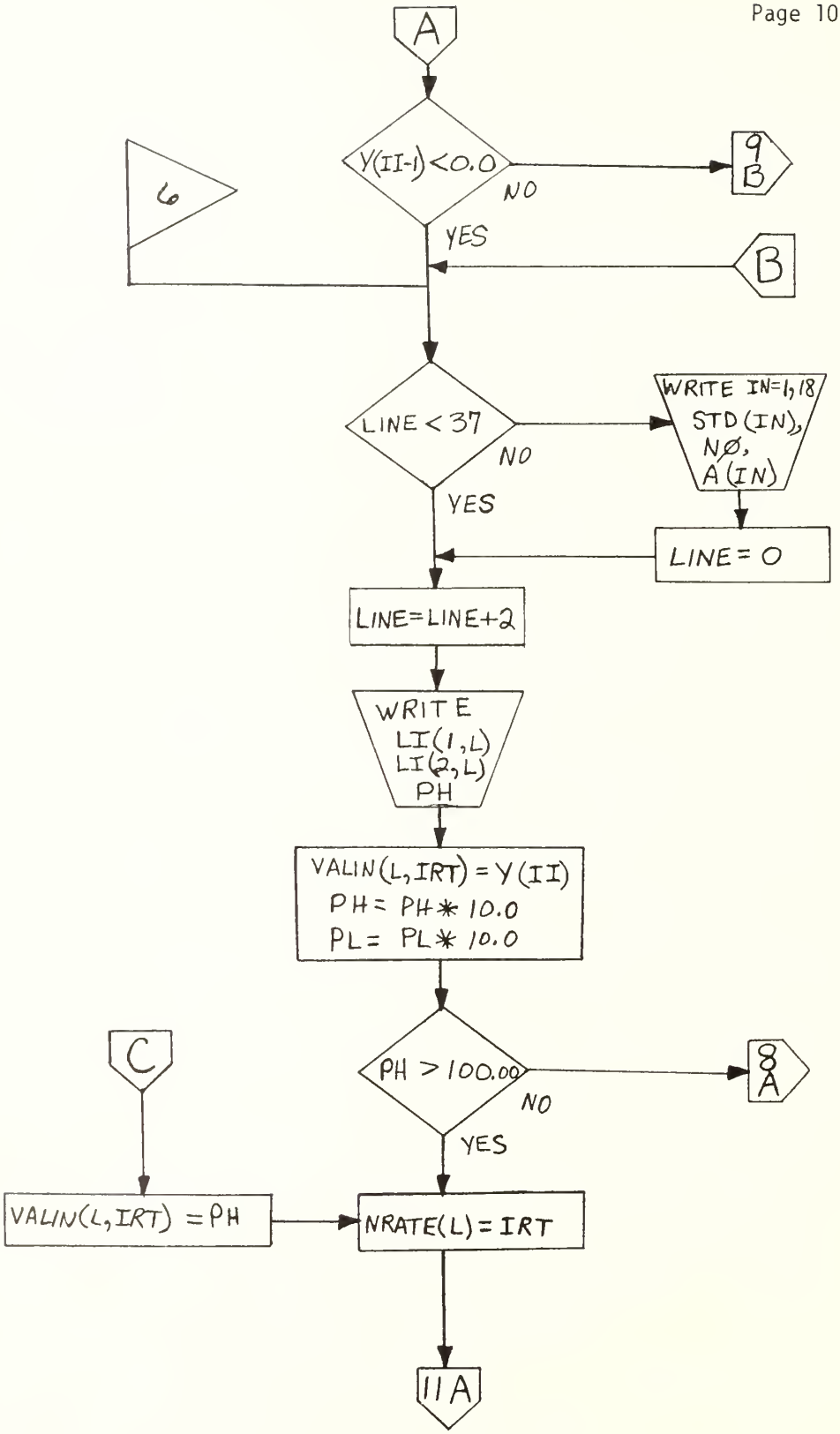

A
DKC = DKC + PECO (L, KC)
DKI = DKI + RETURN (L, KC)
5
VALIN(L,I) = DKI - DKC
3B
3
B
IRT = NR
NRATE(L) = IRT
XRATE(L,IRT) = FRATE
LR = 1
LINE < 37
NO
YES
WRITE IN=1,18
STD (IN)
NO
A(IN)
LINE = 0
LINE = LINE + 1
WRITE
L
11B

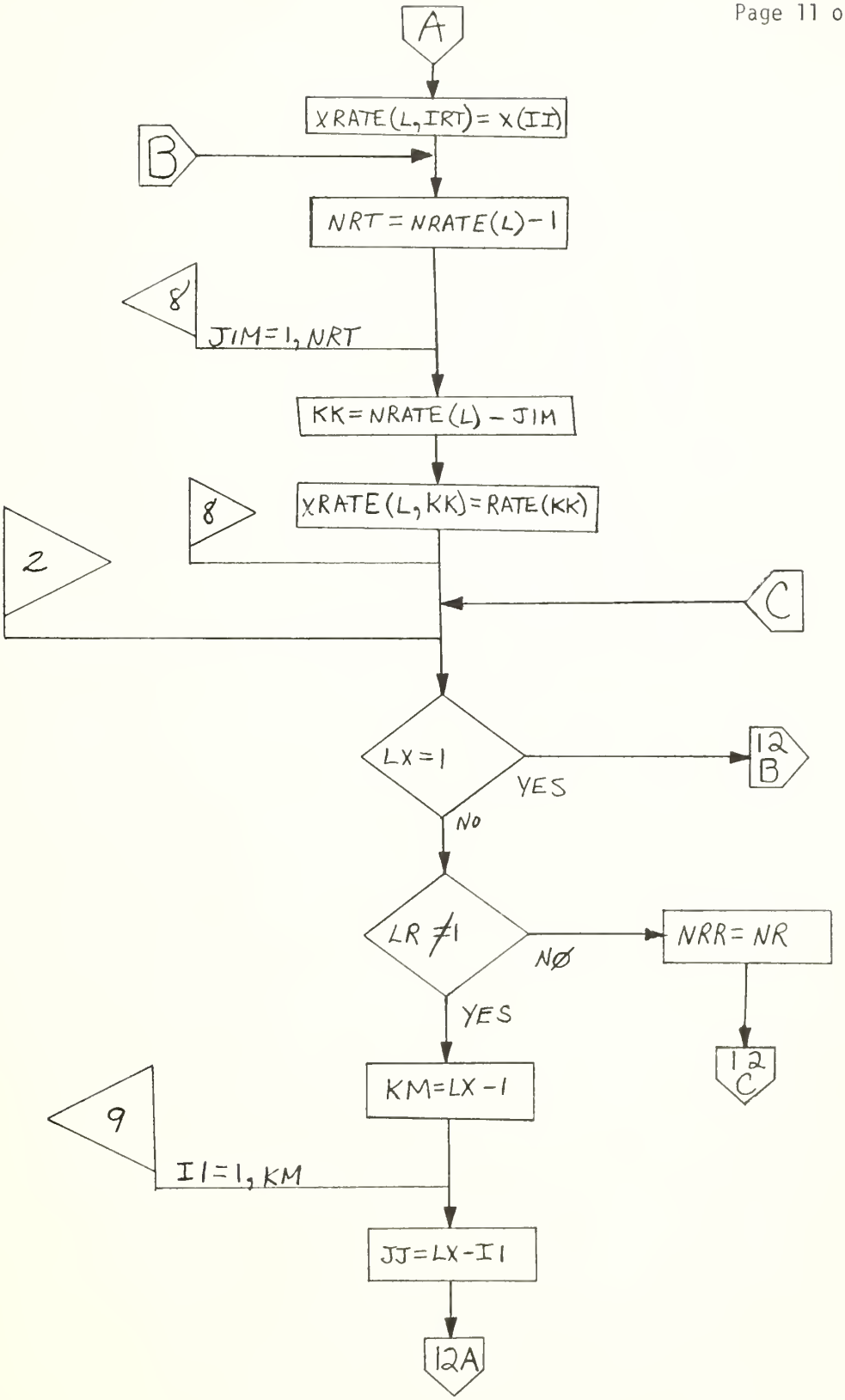

A
IRT=I
NRATE(L)=IRT
XRATE(L,IRT)=RATE(IRT)
VALIN(L,IRT) ≤0.01
AND
VALIN(L,IRT) ≥-0.01
NO
11
B
YES
VALIN(L,IRT)=0.0
NRATE(L)=1
NO
11
B
YES
11C

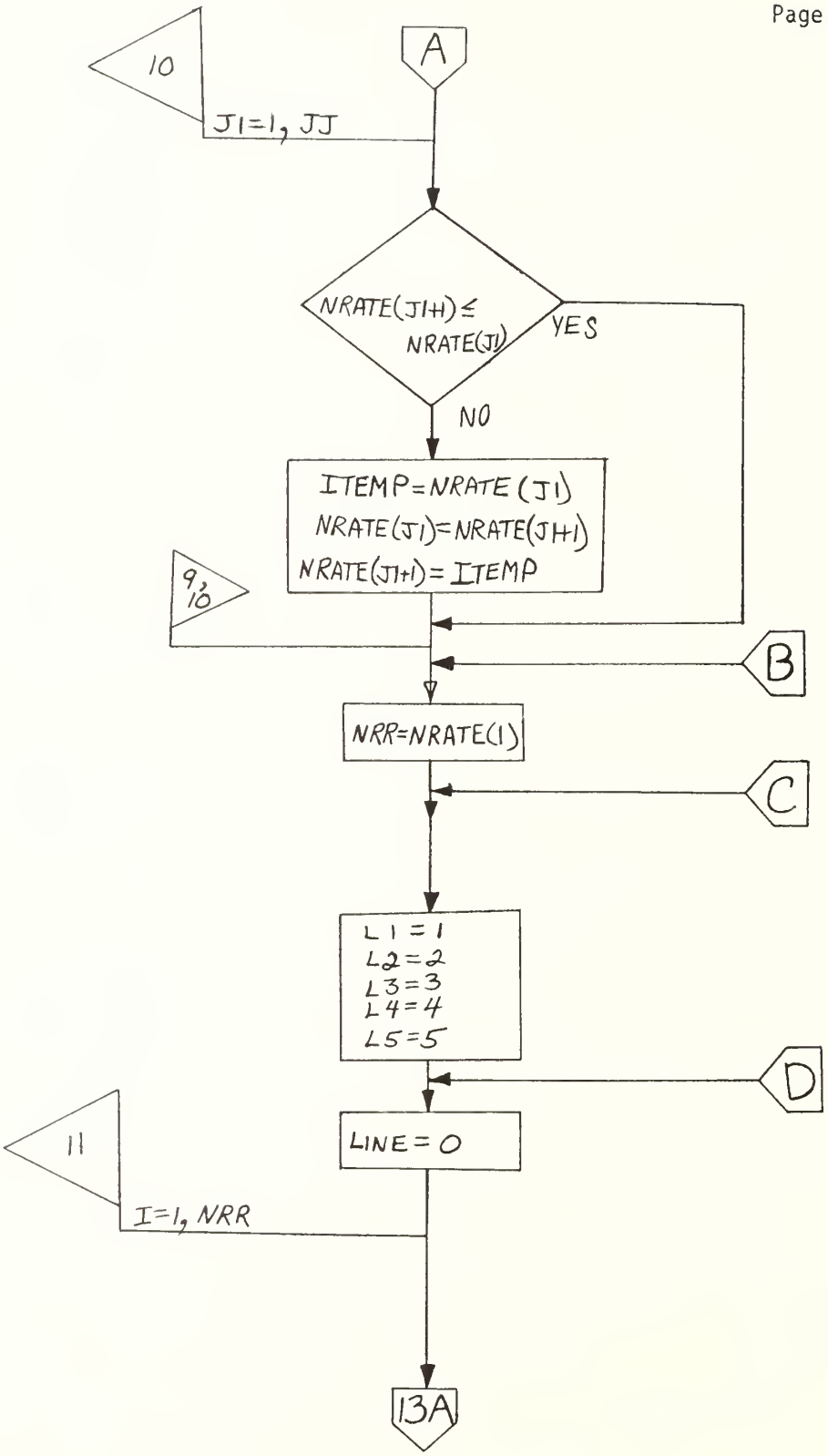

B
PH=1.00
PL=-1.00
8A

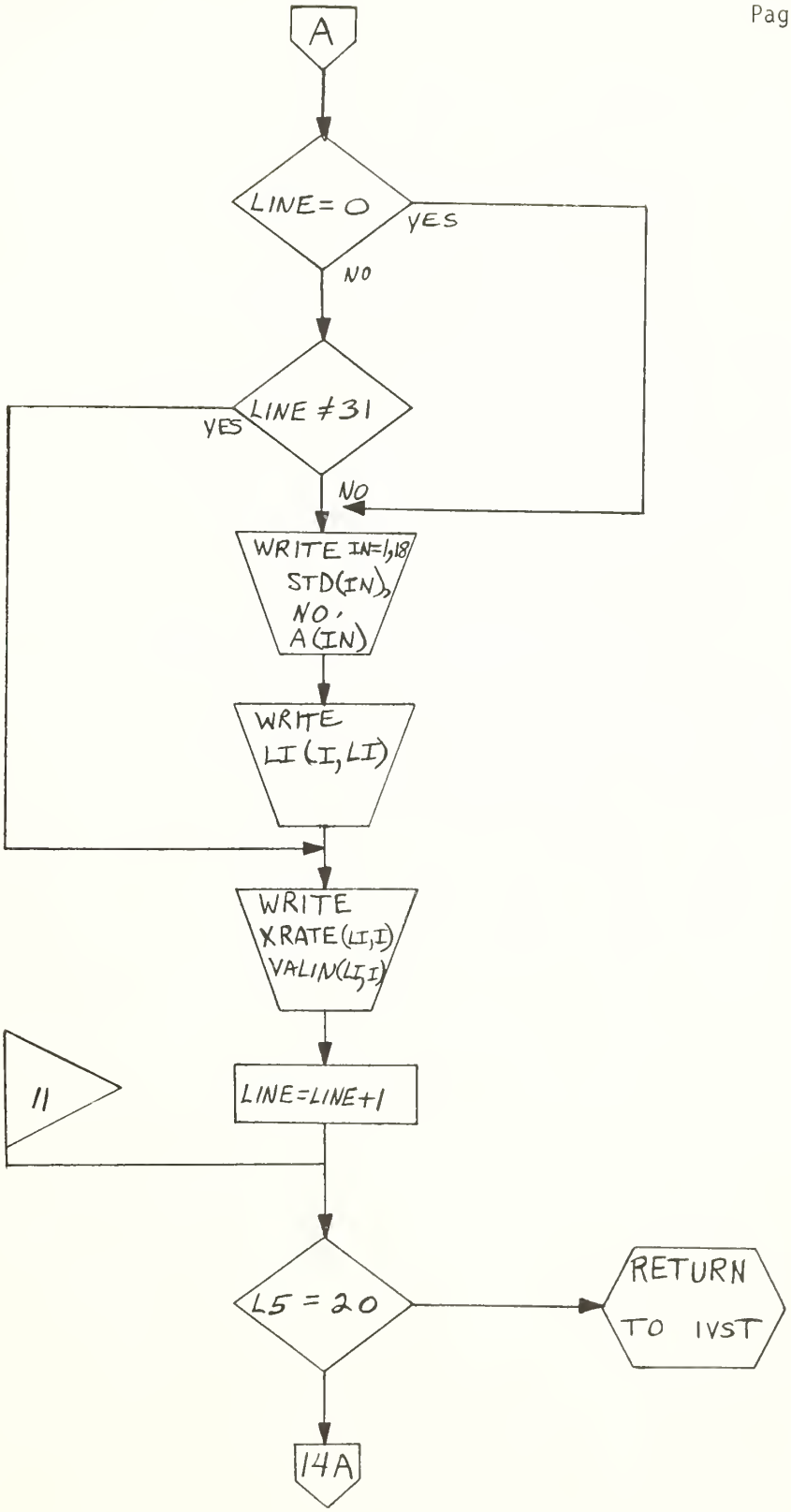

A
IRT=I
Y(1)= VALIN (L,IRT)
Y(2)= VALIN(L,IRT-1)
X(1)= RATE (IRT)
X(2)= RATE (IRT-1)
6
II=3, 100
X(II-2)=X(II-1)
YES
10
B
NO
X(II)=(X(II-2)+X(II-1))/2.0
RLOG= ALOG (1.0+X(II))
DISCO= EXP (RLOG * XLY)
DKC = 0.0
DKI = 0.0
7
KC=1, KCXA
DKC= DKC+ PECO(L,KC)/EXP(RLOG*YR(L,KC))
DKI= DKI+RETURN(L,KC)/EXP(RLOG * YR(L,KC))
7
9A

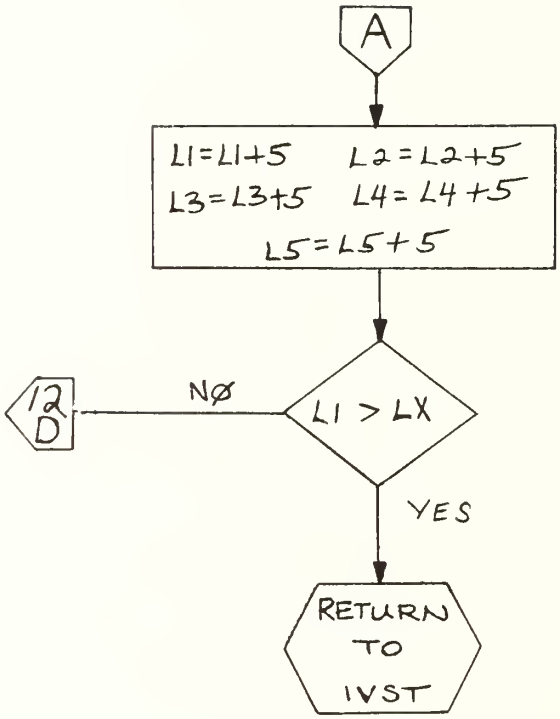

A
TDVAL = DK1 − DKC
NZ = 2
NO
Y(II) = TDVAL * (1.0 + 1.0 / (DISCO − 1.0))
YES
Y(II) = TDVAL
Y(II) ≤ PH AND Y(II) ≥ PL
YES
10 C
NO
Y(II)
>0
10A
=0
10 C
<0
Y(II-1) > 0.0
YES
10 B
NO
B
Y(II-1) = Y(II-2)
X(II-1) = X(II-2)
10 B


A
Y(II-1)<0.0
NO
9
B
YES
6
B
LINE < 37
NO
WRITE IN=1,18
STD(IN),
NØ,
A(IN)
YES
LINE = 0
LINE=LINE+2
WRITE
LI(1,L)
LI(2,L)
PH
VALIN(L,IRT) = Y(II)
PH = PH * 10.0
PL = PL * 10.0
C
PH > 100.00
NO
8
A
YES
VALIN(L,IRT) = PH
NRATE(L) = IRT
11A


A
XRATE(L,IRT)=X(II)
B
NRT=NRATE(L)-1
8
JIM=1,NRT
KK=NRATE(L)-JIM
8
XRATE(L,KK)=RATE(KK)
2
C
LX=1
YES
12
B
NO
LR≠1
NØ
NRR=NR
12
C
YES
KM=LX-1
9
I1=1,KM
JJ=LX-I1
12A


10
A
J1=1, JJ
NRATE(J1+1) ≤ NRATE(J1)
YES
NO
ITEMP=NRATE(J1)
NRATE(J1)=NRATE(J1+1)
NRATE(J1+1)=ITEMP
9, 10
B
NRR=NRATE(1)
C
L1=1
L2=2
L3=3
L4=4
L5=5
D
11
LINE=0
I=1, NRR
13A


A
LINE=0
YES
NO
LINE≠31
YES
NO
WRITE IN=1,18
STD(IN),
NO,
A(IN)
WRITE
LI(I,LI)
WRITE
XRATE(LI,I)
VALIN(LI,I)
11
LINE=LINE+1
L5=20
RETURN
TO IVST
14A


A
L1=L1+5 L2=L2+5
L3=L3+5 L4=L4+5
L5=L5+5
L1 > LX
NØ
12 D
YES
RETURN TO IVST

IVST SOURCE PROGRAM

```
C INVESTMENT ANALYSIS PROGRAM                                                  IVST0000
C PROGRAM IVST                                    MAY 1968                     IVST0005
C BY D.E. CHAPPELLE                                                            IVST0010
C PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION                        IVST0015
C                                                                              IVST0020
C MAIN PROGRAM TO CALL IROR AND BCA SUBROUTINES                                IVST0025
C                                                                              IVST0030
C                                                                              IVST0035
C                                                                              IVST0040
C                                                                              IVST0045
C                                    SYMBOL TABLE                              IVST0050
C     A(I)=ALPHANUMERIC PROBLEM IDENTIFICATION (1-72 CHARACTERS)               IVST0055
C     BRATE=BEGINNING INTEREST RATE (MUST BE GREATER THAN -100 PERCENT),IVST0060
C          DECIMAL                                                             IVST0065
C     COST(L,KC)=PERIODIC ANNUAL COST OF ALTERNATIVE L, FOR PERIOD KC,         IVST0070
C                DOLLARS.                                                      IVST0075
C     DELTA=RATE INCREMENT, DECIMAL                                            IVST0080
C     FRATE=FINAL INTEREST RATE, DECIMAL                                       IVST0085
C     INIT=INITIAL VALUE CODE                                                  IVST0086
C         =0, IF THERE IS AN INITIAL COST OR RETURN                            IVST0087
C         =1, IF NOT                                                           IVST0088
C     NOTE--WHEN INIT=0, IP MUST EQUAL 1                                       IVST0089
C     INVESTMENT CRITERION                                                     IVST0090
C         IC=01, INTERNAL RATE OF RETURN                                       IVST0095
C         IC=02, BENEFIT/COST AND PRESENT NET WORTH                            IVST0100
C         IC=03, ALL THREE CRITERIA                                            IVST0105
C     IP=LENGTH OF PERIOD OVER WHICH ONE COST OR RETURN APPLIES,               IVST0110
C        YEARS (1-140). PERIOD MUST BE THE SAME FOR ALL ALTERNATIVES           IVST0115
C        WITHIN A PROBLEM.                                                     IVST0120
C     KCT=NUMBER OF PERIODS (1-140)                                            IVST0125
C     KCX(L)=NUMBER OF YEARS IN EACH ALTERNATIVE L (1-140)                     IVST0130
C     KCXX=MAXIMUM NUMBER OF YEARS IN ANY ALTERNATIVE (1-140)                  IVST0135
C     LI(1,L), LI(2,L)=ALPHANUMERIC IDENTIFICATION OF ALTERNATIVE L            IVST0140
C          (1-8 CHARACTERS)                                                    IVST0145
C     LX=NUMBER OF ALTERNATIVES WITHIN PROBLEM (1-20)                          IVST0150
C     MEND=TERMINAL CARD CODE---98, TO DO ANOTHER PROBLEM                      IVST0155
C                               99, END-OF-RUN                                 IVST0160
C                                                                              IVST0165
C     NO=PROBLEM NUMBER                                                        IVST0170
C     REV(L,KC)=PERIODIC ANNUAL VALUE YIELD OF PRODUCT IN ALTERNATIVE L,IVST0175
```

```
C                FOR PERIOD KC, DOLLARS.                                        IVST0180
C      STD(I)=ALPHANUMERIC STUDY IDENTIFICATION (1-72 CHARACTERS)               IVST0185
C      TYPE OF CALCULATION-                                                     IVST0190
C           NZ=01, IF PERPETUAL SERIES.                                         IVST0195
C           NZ=02, IF TERMINABLE SERIES.                                        IVST0200
C           TYPE OF CALCULATION MUST BE THE SAME FOR ALL ALTERNATIVES           IVST0205
C           WITHIN A PROBLEM.                                                   IVST0210
C      YR(L,LZ)=YEAR IN WHICH LTH COST AND RETURN OCCURS (1-140).               IVST0215
C                                                                               IVST0220
C                                                                               IVST0225
C                                                                               IVST0230
C                                                                               IVST0235
       INTEGER COST(20,140), REV(20,140)                                        IVST0240
       DIMENSION KCX(20),RTLOG(200),PECO(20,140),RETURN(20,140),LI(2,20),IVST0245
      1A(18),STD(18),YR(20,140),RATE(200)                                       IVST0250
      2,BCR(20,200),VALIN(20,200)                                               IVST0255
       COMMON KCX,RTLOG,PECO,RETURN,LI,A,STD,YR,NZ,RATE,NR,LX,BCR,VALIN,IVST0260
      1NO,FRATE                                                                 IVST0265
C                                                                               IVST0270
C  INPUT FORMATS                                                                IVST0275
C                                                                               IVST0280
  100 FORMAT (3F10.2,2I5)                                                       IVST0285
  105 FORMAT (10(2A4))                                                          IVST0290
  110 FORMAT (20I3)                                                             IVST0295
  115 FORMAT (5I4)                                                              IVST0300
  120 FORMAT (I3)                                                               IVST0305
  125 FORMAT (8I10)                                                             IVST0310
  130 FORMAT (18A4)                                                             IVST0315
C                                                                               IVST0320
C  OUTPUT FORMATS                                                               IVST0325
C                                                                               IVST0330
  135 FORMAT (1H1,19X,21HINVESTMENT ANALYSIS--,18A4/1H0,11HPROBLEM NO.,IVST0335
     1I3,6X,18A4)                                                               IVST0340
  140 FORMAT (1H0, 17HTERMINABLE SERIES,85X,8HPERIOD= ,I3,6H YEARS)             IVST0345
  145 FORMAT (1H ,52X,22HMANAGEMENT ALTERNATIVE)                                IVST0350
  150 FORMAT (1H0,16HPERPETUAL SERIES,84X,8HPERIOD= ,I4,6H YEARS)               IVST0355
  155 FORMAT(1H0,60X,10HEND OF RUN)                                             IVST0360
  160 FORMAT(1H0,3X,6HPERIOD,2X,5(6HANNUAL,5X,6HANNUAL,7X)/13X,4(4HCOST,IVST0365
     16X,6HRETURN,8X),4HCOST,6X,6HRETURN)                                       IVST0370
  165 FORMAT (1H ,16X,2A4,4(16X,2A4))                                           IVST0375
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```
  170 FORMAT (1H ,3X,I3,5(1X,I10,1X,I10,2X))                          IVST0380
C                                                                     IVST0385
C READ STUDY IDENTIFICATION CARD                                      IVST0390
C                                                                     IVST0395
      READ (5,130) (STD(I),I=1,18)                                    IVST0400
C                                                                     IVST0405
C READ RATE CARD                                                      IVST0410
C                                                                     IVST0415
  175 READ (5,100) BRATE,FRATE,DELTA,LX,INIT                          IVST0420
C                                                                     IVST0425
C  READ PROBLEM NO. AND ALTERNATIVE TITLE CARDS                       IVST0430
C                                                                     IVST0435
      READ (5,105) ((LI(I,L),I=1,2),L=1,LX)                           IVST0440
      READ (5,115) NO,NZ,IC,IP,KCXX                                   IVST0445
      READ (5,110) (KCX(L),L=1,LX)                                    IVST0450
      KCT=KCXX/IP                                                     IVST0455
      DO 180 L=1,LX                                                   IVST0460
      DO 180 KC=1,KCT                                                 IVST0465
      COST(L,KC) = 0                                                  IVST0470
      REV(L,KC) = 0                                                   IVST0475
  180 CONTINUE                                                        IVST0480
      IF(BRATE.NE.0.0.AND.FRATE.NE.0.0) GO TO 185                     IVST0485
      IF(NZ.EQ.2) GO TO 185                                           IVST0490
      IF(BRATE.EQ.0.0) BRATE=BRATE+DELTA                              IVST0495
      IF(FRATE.EQ.0.0) FRATE=FRATE-DELTA                              IVST0500
C                                                                     IVST0505
C  CALCULATE NUMBER RATES (NR), RATE(I),I=1,NR) AND                   IVST0510
C                  LOG(1.+RATE(I) WHICH IS RTLOG(I) IN PROGRAM        IVST0515
C                                                                     IVST0520
  185 NR=((FRATE-BRATE)/DELTA)+1.05                                   IVST0525
      RATE(1)=BRATE                                                   IVST0530
      RTLOG(1)=ALOG(1.0+RATE(1))                                      IVST0535
      DO 195 I=2,NR                                                   IVST0540
      RATE(I)=RATE(I-1)+DELTA                                         IVST0545
      IF(RATE(I).NE.0.0)   GO TO 190                                  IVST0550
      IF(NZ.EQ.2) GO TO 190                                           IVST0555
      RATE(I)=RATE(I)+DELTA                                           IVST0560
  190 RTLOG(I)=ALOG(1.0+RATE(I))                                      IVST0565
  195 CONTINUE                                                        IVST0570
C                                                                     IVST0575
```

```
C  READ PROBLEM IDENTIFICATION CARD                                          IVST0580
C                                                                           IVST0585
      READ(5,130)(A(I),I=1,18)                                              IVST0590
C                                                                           IVST0595
C  READ PERIODIC ANNUAL COSTS AND RETURNS                                   IVST0600
C                                                                           IVST0605
      DO 200 L=1,LX                                                         IVST0610
      KCS = KCX(L)/IP                                                       IVST0615
      READ (5,125) (COST(L,KC),KC=1,KCS)                                    IVST0620
      READ (5,125) (REV(L,KC),KC=1,KCS)                                     IVST0625
  200 CONTINUE                                                              IVST0630
C                                                                           IVST0635
C  WRITE PERIODIC ANNUAL COSTS AND RETURNS                                  IVST0640
C                                                                           IVST0645
      L1=1                                                                  IVST0650
      L2=2                                                                  IVST0655
      L3=3                                                                  IVST0660
      L4=4                                                                  IVST0665
      L5=5                                                                  IVST0670
  205 LINE=0                                                                IVST0675
  210 DO 245  K=1,KCT                                                       IVST0680
  215 IF(LINE.NE.0) GO TO 235                                               IVST0685
  220 WRITE (6,135) (STD(I),I=1,18),NO,(A(I),I=1,18)                        IVST0690
      IF (NZ.EQ.1) GO TO 225                                                IVST0695
      WRITE (6,140) IP                                                      IVST0700
      GO TO 230                                                             IVST0705
  225 WRITE (6,150) IP                                                      IVST0710
  230 WRITE (6,145)                                                         IVST0715
      WRITE (6,165) LI(1,L1),LI(2,L1),LI(1,L2),LI(2,L2),LI(1,L3),LI(2,L3IVST0720
     1),LI(1,L4),LI(2,L4),LI(1,L5),LI(2,L5)                                 IVST0725
      WRITE (6,160)                                                         IVST0730
  235 KC=K                                                                  IVST0731
      KT=K                                                                  IVST0732
      IF(IP.EQ.1.AND.INIT.EQ.0) KT=K-1                                      IVST0733
      WRITE (6,170) KT,COST(L1,KC),REV(L1,KC),COST(L2,KC),REV(L2,KC),COSIVST0735
     1T(L3,KC),REV(L3,KC),COST(L4,KC),REV(L4,KC),COST(L5,KC),REV(L5,KC) IVST0740
  240 LINE=LINE+1                                                           IVST0745
      IF (LINE.EQ.31) LINE=0                                                IVST0750
  245 CONTINUE                                                              IVST0755
      IF (L5.EQ.20) GO TO 250                                               IVST0760
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```
      L1=L1+5                                                          IVST0765
      L2=L2+5                                                          IVST0770
      L3=L3+5                                                          IVST0775
      L4=L4+5                                                          IVST0780
      L5=L5+5                                                          IVST0785
      IF (L1.GT.LX) GO TO 250                                          IVST0790
      GO TO 205                                                        IVST0795
C                                                                      IVST0800
C  GENERATE ANNUAL COSTS AND RETURNS                                   IVST0805
C                                                                      IVST0810
  250 DO 265 L=1,LX                                                    IVST0815
      LZ=0                                                             IVST0820
      DO 260 KC=1,KCT                                                  IVST0825
      LXX=0                                                            IVST0830
  255 LZ=LZ+1                                                          IVST0835
      PECO(L,LZ)=COST(L,KC)                                            IVST0840
      RETURN(L,LZ)=REV(L,KC)                                           IVST0845
      YR(L,LZ)=LZ                                                      IVST0850
      IF(IP.EQ.1.AND.INIT.EQ.0) YR(L,LZ)=YR(L,LZ)-1.0                  IVST0851
      LXX=LXX+1                                                        IVST0855
      IF (LXX.LT.IP) GO TO 255                                         IVST0860
  260 CONTINUE                                                         IVST0865
  265 CONTINUE                                                         IVST0870
C                                                                      IVST0875
C                                                                      IVST0880
C  CALL INVESTMENT CRITERION                                           IVST0885
      IF (IC.EQ.03.OR.IC.EQ.02) CALL BCA                               IVST0890
      IF (IC.EQ.03.OR.IC.EQ.01) CALL IROR                              IVST0895
C                                                                      IVST0900
C  READ TERMINAL CARD                                                  IVST0905
C                                                                      IVST0910
  270 READ(5,120) MEND                                                 IVST0915
      IF(MEND.EQ.99) GO TO 275                                         IVST0920
      GO TO 175                                                        IVST0925
  275 WRITE(6,155)                                                     IVST0930
      STOP                                                             IVST0935
      END                                                              IVST0940
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```
C BENEFIT/COST AND PRESENT NET WORTH ANALYSIS                                    BCA 0000
C SUBROUTINE BCA                                MAY 1968                        BCA 0005
C BY D.E. CHAPPELLE                                                             BCA 0010
C PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION                         BCA 0015
C                                                                               BCA 0020
C CALLED BY PROGRAM IVST                                                        BCA 0025
      SUBROUTINE BCA                                                            BCA 0030
      DIMENSION KCX(20),YR(20,140),BCR(20,200),RATE(200),                       BCA 0035
     1RTLOG(200),PECO(20,140),RETURN(20,140),LI(2,20),                          BCA 0040
     2A(18), VALIN(20,200),STD(18)                                              BCA 0045
      COMMON KCX,RTLOG,PECO,RETURN,LI,A,STD,YR,NZ,RATE,NR,LX,BCR,VALIN,         BCA 0050
     1NO,FRATE                                                                  BCA 0055
C                                                                               BCA 0060
C OUTPUT FORMATS                                                                BCA 0065
C                                                                               BCA 0070
  100 FORMAT (1H1)                                                              BCA 0075
  105 FORMAT (1H1,19X,23HBENEFIT-COST ANALYSIS--,18A4,/1H0,11HPROBLEM NOBCA 0080
     1.,I3,6X,18A4)                                                             BCA 0085
  110 FORMAT (1H0,52X,22HMANAGEMENT ALTERNATIVE)                                BCA 0090
  115 FORMAT (1H0,57HBENEFIT-COST RATIO (B/C) AT ALTERNATIVE RATES OF INBCA 0095
     1TEREST,/,1H ,56HPRESENT NET WORTH (PNW) AT ALTERNATIVE RATES OF INBCA 0100
     2TEREST)                                                                   BCA 0105
  120 FORMAT (1H ,21X,2A4,4(15X,2A4),/,1H0,2X,4HRATE,10X,4H*PNW,8X,4HB/CBCA 0110
     1*,4(8X,4H*PNW,8X,4HB/C*),//)                                              BCA 0115
  125 FORMAT (2PF7.2,4X,0PE13.4,F9.2,4(2X,E13.4,F9.2))                          BCA 0120
C                                                                               BCA 0125
      WRITE (6,100)                                                             BCA 0130
C                                                                               BCA 0135
C CLEAR ARRAY FOR  PRESENT NET WORTH (VALIN(L,I)) AND BENEFIT-COST              BCA 0140
C RATIO (BCR(L,I)) ARRAY                                                        BCA 0145
C                                                                               BCA 0150
      DO 130 LLL=1,LX                                                           BCA 0155
      DO 130 III=1,NR                                                           BCA 0160
      VALIN(LLL,III) = 0.0                                                      BCA 0165
      BCR(LLL,III)=0.0                                                          BCA 0170
  130 CONTINUE                                                                  BCA 0175
C                                                                               BCA 0180
C  BEGINNING OF L-LOOP (ALTERNATIVES)                                           BCA 0185
C                                                                               BCA 0190
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      DO 175 L=1,LX                                                    BCA 0195
      KCXA=KCX(L)                                                      BCA 0200
      XLY=FLOAT(KCX(L))                                                BCA 0205
      IF (KCXA.EQ.0) GO TO 175                                         BCA 0210
C                                                                      BCA 0215
C  BEGINNING I-LOOP (RATES OF RETURN)                                  BCA 0220
C                                                                      BCA 0225
  135 DO 175 I=1,NR                                                    BCA 0230
      DKC=0.0                                                          BCA 0235
      DK1=0.0                                                          BCA 0240
      IF(RTLOG(I).EQ.0.0) GO TO 145                                    BCA 0245
C                                                                      BCA 0250
C  CALCULATE DISCOUNTED COST AND RETURN                                BCA 0255
C                                                                      BCA 0260
      DO 140 KC=1,KCXA                                                 BCA 0265
      DKC=DKC+PECO(L,KC)/EXP(RTLOG(I)*YR(L,KC))                        BCA 0270
      DK1=DK1+RETURN(L,KC)/EXP(RTLOG(I)*YR(L,KC))                      BCA 0275
  140 CONTINUE                                                         BCA 0280
      GO TO 155                                                        BCA 0285
  145 DO 150 KC=1,KCXA                                                 BCA 0290
      DKC=DKC+PECO(L,KC)                                               BCA 0295
      DK1=DK1+RETURN(L,KC)                                             BCA 0300
  150 CONTINUE                                                         BCA 0305
C                                                                      BCA 0310
C CALCULATE PRESENT NET WORTH (VALIN) AND BENEFIT-COST RATIO (B/C)     BCA 0315
C                                                                      BCA 0320
  155 IF (NZ.EQ.2) GO TO 160                                           BCA 0325
      DISCO=EXP(RTLOG(I)*XLY)                                          BCA 0330
      DIS=(1.0+1.0/(DISCO-1.0))                                        BCA 0335
      DK1=DK1*DIS                                                      BCA 0340
      DKC=DKC*DIS                                                      BCA 0345
  160 VALIN(L,I) = DK1 - DKC                                           BCA 0350
C                                                                      BCA 0355
C  IF USER DESIRES TO PRINT DISCOUNTED RETURNS AND COSTS, REMOVE THE C BCA 0360
C  FROM COLUMN 1 OF THE NEXT 2 CARDS                                   BCA 0365
C     WRITE(6,162) DK1,DKC                                             BCA 0370
C 162 FORMAT (1H ,E15.4,10X,E15.4)                                     BCA 0375
      IF (DK1.EQ.0.0.OR.DKC.EQ.0.0) GO TO 170                          BCA 0380
      IF (DK1.GT.0.0) GO TO 165                                        BCA 0385
      IF (DKC.GT.0.0) GO TO 170                                        BCA 0390
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      BCR(L,I) = DKC / DK1                                                  BCA 0395
      GO TO 175                                                             BCA 0400
  165 IF (DKC.LT.0.0) GO TO 170                                             BCA 0405
      BCR(L,I) = DK1 / DKC                                                  BCA 0410
      GO TO 175                                                             BCA 0415
  170 BCR(L,I) = 0.0                                                        BCA 0420
  175 CONTINUE                                                              BCA 0425
C                                                                           BCA 0430
C  END OF I-LOOP                                                            BCA 0435
C  END OF L-LOOP                                                            BCA 0440
C                                                                           BCA 0445
C WRITE BENEFIT-COST RATIO                                                  BCA 0450
C                                                                           BCA 0455
      L1=1                                                                  BCA 0460
      L2=2                                                                  BCA 0465
      L3=3                                                                  BCA 0470
      L4=4                                                                  BCA 0475
      L5=5                                                                  BCA 0480
  180 LINE=0                                                                BCA 0485
      DO 195 I=1,NR                                                         BCA 0490
      IF(LINE.EQ.0) GO TO 185                                               BCA 0495
      IF (LINE.NE.31) GO TO 190                                             BCA 0500
  185 WRITE (6,105) (STD(IN),IN=1,18), NO, (A(IN),IN=1,18)                  BCA 0505
      WRITE (6,115)                                                         BCA 0510
      WRITE (6,110)                                                         BCA 0515
      WRITE (6,120) LI(1,L1),LI(2,L1),LI(1,L2),LI(2,L2),LI(1,L3),LI(2,L3BCA 0520
     1),LI(1,L4),LI(2,L4),LI(1,L5),LI(2,L5)                                 BCA 0525
  190 WRITE (6,125) RATE(I),VALIN(L1,I),BCR(L1,I),VALIN(L2,I),BCR(L2,I),BCA 0530
     1VALIN(L3,I),BCR(L3,I),VALIN(L4,I),BCR(L4,I),VALIN(L5,I),BCR(L5,I)     BCA 0535
      LINE=LINE+1                                                           BCA 0540
  195 CONTINUE                                                              BCA 0545
      IF(L5.EQ.20) RETURN                                                   BCA 0550
      L1=L1+5                                                               BCA 0555
      L2=L2+5                                                               BCA 0560
      L3=L3+5                                                               BCA 0565
      L4=L4+5                                                               BCA 0570
      L5=L5+5                                                               BCA 0575
      IF (L1.GT.LX) RETURN                                                  BCA 0580
      GO TO 180                                                             BCA 0585
      END                                                                   BCA 0590
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      700
C DETERMINING RATE OF RETURN                                                IROR0000
C SUBROUTINE IROR                              MAY 1968                     IROR0005
C BY D.E. CHAPPELLE                                                         IROR0010
C PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION                     IROR0015
C                                                                           IROR0020
C CALLED BY PROGRAM IVST                                                    IROR0025
C                                                                           IROR0030
C (BASED ON SOUTHERN FOREST EXPERIMENT STATION INVESTMENT ANALYSIS          IROR0035
C PROGRAM BY CLARK ROW)                                                     IROR0040
C                                                                           IROR0045
C BISECTION METHOD IS USED TO DETERMINE RATE AT WHICH DISCOUNTED NET        IROR0050
C WORTH APPROACHES 0.0                                                      IROR0055
C                                                                           IROR0060
C PRECISION LEVELS ARE VARIED WITHIN THE BISECTION ANALYSIS                 IROR0065
C                                                                           IROR0070
C THE PRECISION APPLICABLE TO THE CALCULATED RATE OF RETURN IS SHOWN        IROR0075
C AS THE LAST ENTRY IN THE PRESENT NET WORTH COLUMN                         IROR0080
C                                                                           IROR0085
      SUBROUTINE IROR                                                       IROR0090
      DIMENSION KCX(20),YR(20,140),VALIN(20,200),X(100),Y(100),NRATE(20)IROR0095
     1,RATE(200),RTLOG(200),PECO(20,140),RETURN(20,140),LI(2,20),          IROR0100
     2A(18),STD(18)                                                        IROR0105
      COMMON KCX,RTLOG,PECO,RETURN,LI,A,STD,YR,NZ,RATE,NR,LX,XRATE(20,20IROR0110
     10),VALIN,NO,FRATE                                                    IROR0115
C                                                                           IROR0120
C  OUTPUT FORMATS                                                           IROR0125
C                                                                           IROR0130
  100 FORMAT (1H0,10X,39HBISECTION LIMIT EXCEEDED IN ALTERNATIVE,2A4/1H IROR0135
     1,10X,66HCALCULATED PRESENT NET WORTH DOES NOT FALL BETWEEN PLUS ANIROR0140
     2D MINUS ,F6.2,8H DOLLARS,/)                                           IROR0145
  105 FORMAT (1H1,19X,28HDETERMINING RATE OF RETURN--,18A4/1H0,11HPROBLEIROR0150
     1M NO.,I3,6X,18A4)                                                     IROR0155
  110 FORMAT (1H0,50X,8HMESSAGES,/)                                         IROR0160
  115 FORMAT (1H0,52X,22HMANAGEMENT ALTERNATIVE,/)                          IROR0165
  120 FORMAT(1H0,56HPRESENT NET WORTH (PNW) AT ALTERNATIVE RATES OF INTEIROR0170
     1REST)                                                                 IROR0175
  125 FORMAT (1H ,5X,2A4,4(20X,2A4)/1H0,4(7H * RATE,7X,5HPNW *,8X),7H * IROR0180
     1RATE,7X,5HPNW *,//)                                                   IROR0185
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  130 FORMAT (4(2PF7.2,1PE13.4,7X),2PF7.2,1PE13.4)                        IROR0190
  135 FORMAT (1H ,10X,76HINTERNAL RATE OF RETURN DOES NOT FALL WITHIN SEIROR0195
     1LECTED RANGE FOR ALTERNATIVE ,I3)                                   IROR0200
  140 FORMAT(1H ,10X,108HPNW AS A FUNCTION OF INTEREST RATE IS NOT TENDIIROR0205
     1NG TOWARD ZERO WITHIN A PORTION OF ITS RANGE FOR ALTERNATIVE ,I3) IROR0210
C                                                                        IROR0215
      WRITE (6,105) (STD(IN),IN=1,18),NO,(A(IN),IN=1,18)                 IROR0220
      LINE=0                                                             IROR0225
      WRITE (6,110)                                                      IROR0230
C                                                                        IROR0235
C  CLEAR ARRAY FOR DISCOUNTED NET WORTH(VALIN(L,I) AND XRATE ARRAY       IROR0240
C                                                                        IROR0245
      DO 145 LLL=1,LX                                                    IROR0250
      DO 145 III=1,NR                                                    IROR0255
      VALIN(LLL,III)=0.0                                                 IROR0260
  145 XRATE(LLL,III)=0.0                                                 IROR0265
C  BEGINNING OF L-LOOP (ALTERNATIVES)                                    IROR0270
C                                                                        IROR0275
      DO 305 L=1,LX                                                      IROR0280
      KCXA=KCX(L)                                                        IROR0285
      XLY = FLOAT(KCX(L))                                                IROR0290
      IF(KCXA.EQ.0) GO TO 305                                            IROR0295
C                                                                        IROR0300
C  BEGINNING I-LOOP (RATES OF RETURN)                                    IROR0305
C                                                                        IROR0310
  150 DO 210 I=1,NR                                                      IROR0315
      DKC=0.0                                                            IROR0320
      DK1=0.0                                                            IROR0325
      IF(RTLOG(I).EQ.0.0) GO TO 195                                      IROR0330
C                                                                        IROR0335
C  CALCULATE DISCOUNTED COST AND RETURN                                  IROR0340
C                                                                        IROR0345
      DO 155 KC=1,KCXA                                                   IROR0350
      DKC=DKC+PFCO(L,KC)/EXP(RTLOG(I)*YR(L,KC))                          IROR0355
      DK1=DK1+RETURN(L,KC)/EXP(RTLOG(I)*YR(L,KC))                        IROR0360
  155 CONTINUE                                                           IROR0365
C                                                                        IROR0370
C  TOTAL DISCOUNTED VALUE (TDVAL)                                        IROR0375
```

```
C                                                                       IROR0380
  160 TDVAL=DK1-DKC                                                     IROR0385
      IF(NZ.EQ.2) GO TO 190                                             IROR0390
C                                                                       IROR0395
C  PRESENT NET WORTH (VALIN)                                            IROR0400
C                                                                       IROR0405
      DISCO=EXP(RTLOG(I)*XLY)                                           IROR0410
      VALIN(L,I)=TDVAL*(1.0+1.0/(DISCO-1.0))                            IROR0415
  165 IF(VALIN(L,I).LE.0.01.AND.VALIN(L,I).GE.(-0.01)) GO TO 225        IROR0420
      IF(I.EQ.1) GO TO 210                                              IROR0425
      IF(VALIN(L,I-1))170,225,180                                       IROR0430
  170 IF(VALIN(L,I).GT.0.0) GO TO 235                                   IROR0435
      IF(VALIN(L,I).GE.VALIN(L,I-1)) GO TO 210                          IROR0440
      IF (LINE.LT.37) GO TO 175                                         IROR0445
      WRITE (6,105) (STD(IN),IN=1,18),NO,(A(IN),IN=1,18)                IROR0450
      LINE=0                                                            IROR0455
  175 LINE=LINE+1                                                       IROR0460
      WRITE (6,140) L                                                   IROR0465
      GO TO 225                                                         IROR0470
  180 IF(VALIN(L,I).LT.0.0)GO TO 235                                    IROR0475
      IF(VALIN(L,I).LE.VALIN(L,I-1)) GO TO 210                          IROR0480
      IF (LINE.LT.37) GO TO 185                                         IROR0485
      WRITE (6,105) (STD(IN),IN=1,18),NO,(A(IN),IN=1,18)                IROR0490
      LINE=0                                                            IROR0495
  185 LINE=LINE+1                                                       IROR0500
      WRITE (6,140) L                                                   IROR0505
      GO TO 225                                                         IROR0510
  190 VALIN(L,I)=TDVAL                                                  IROR0515
      GO TO 165                                                         IROR0520
  195 DO 200 KC=1,KCXA                                                  IROR0525
      DKC=DKC+PECO(L,KC)                                                IROR0530
      DK1=DK1+RETURN(L,KC)                                              IROR0535
  200 CONTINUE                                                          IROR0540
  205 VALIN(L,I)=DK1-DKC                                                IROR0545
      GO TO 165                                                         IROR0550
  210 CONTINUE                                                          IROR0555
C                                                                       IROR0560
C  END OF I-LOOP                                                        IROR0565
```

```
C                                                                       IROR0570
  215 IRT=NR                                                            IROR0575
      NRATE(L)=IRT                                                      IROR0580
      XRATE(L,IRT)=FRATE                                                IROR0585
      LR = 1                                                            IROR0590
      IF (LINE.LT.37) GO TO 220                                         IROR0595
      WRITE (6,105) (STD(IN),IN=1,18),NO,(A(IN),IN=1,18)                IROR0600
      LINE=0                                                            IROR0605
  220 LINE=LINE+1                                                       IROR0610
      WRITE (6,135) L                                                   IROR0615
      GO TO 295                                                         IROR0620
  225 IRT=I                                                             IROR0625
      NRATE(L)=IRT                                                      IROR0630
      XRATE(L,IRT)=RATE(IRT)                                            IROR0635
      IF(VALIN(L,IRT).LE.0.01.AND.VALIN(L,IRT).GE.(-0.01)) GO TO 230    IROR0640
      GO TO 295                                                         IROR0645
  230 VALIN(L,IRT)=0.0                                                  IROR0650
      IF(NRATE(L).EQ.1) GO TO 305                                       IROR0655
      GO TO 295                                                         IROR0660
C                                                                       IROR0665
C  BEGINNING BISECTION COMPUTATION                                      IROR0670
C                                                                       IROR0675
  235 PH=1.00                                                           IROR0680
      PL=-1.00                                                          IROR0685
  240 IRT=I                                                             IROR0690
      Y(1)=VALIN(L,IRT)                                                 IROR0695
      Y(2)=VALIN(L,IRT-1)                                               IROR0700
      X(1)=RATE(IRT)                                                    IROR0705
      X(2)=RATE(IRT-1)                                                  IROR0710
      DO 275 II=3,100                                                   IROR0715
      IF(X(II-2).EQ.X(II-1)) GO TO 275                                  IROR0720
      X(II)=(X(II-2)+X(II-1))/2.0                                       IROR0725
      RLOG=ALOG(1.0+X(II))                                              IROR0730
      DISCO=EXP(RLOG*XLY)                                               IROR0735
      DKC=0.0                                                           IROR0740
      DK1=0.0                                                           IROR0745
      DO 245 KC=1,KCXA                                                  IROR0750
      DKC=DKC+PECO(L,KC)/EXP(RLOG*YR(L,KC))                             IROR0755
      DK1=DK1+RETURN(L,KC)/EXP(RLOG*YR(L,KC))                           IROR0760
  245 CONTINUE                                                          IROR0765
```

```
      TDVAL=DK1-DKC                                                    IROR0770
      IF (NZ.EQ.2) GO TO 250                                           IROR0775
      Y(II)=TDVAL*(1.0+1.0/(DISCO-1.0))                                IROR0780
      GO TO 255                                                        IROR0785
  250 Y(II)=TDVAL                                                      IROR0790
  255 IF(Y(II).LE.PH.AND.Y(II).GE.PL) GO TO 285                        IROR0795
      IF(Y(II)) 260,285,270                                            IROR0800
  260 IF(Y(II-1).GT.0.0) GO TO 275                                     IROR0805
  265 Y(II-1)=Y(II-2)                                                  IROR0810
      X(II-1)=X(II-2)                                                  IROR0815
      GO TO 275                                                        IROR0820
  270 IF(Y(II-1).LT.0.0) GO TO 275                                     IROR0825
      GO TO 265                                                        IROR0830
  275 CONTINUE                                                         IROR0835
C                                                                      IROR0840
C  END OF BISECTION                                                    IROR0845
C                                                                      IROR0850
      IF (LINE.LT.37) GO TO 280                                        IROR0855
      WRITE (6,105) (STD(IN),IN=1,18),NO,(A(IN),IN=1,18)               IROR0860
      LINE=0                                                           IROR0865
  280 LINE=LINE+2                                                      IROR0870
      WRITE (6,100) LI(1,L), LI(2,L), PH                               IROR0875
      VALIN(L,IRT)=Y(II)                                               IROR0880
      PH=PH*10.0                                                       IROR0885
      PL=PL*10.0                                                       IROR0890
      IF(PH.GT.100.00) GO TO 290                                       IROR0895
      GO TO 240                                                        IROR0900
  285 VALIN(L,IRT)=PH                                                  IROR0905
  290 NRATE(L)=IRT                                                     IROR0910
      XRATE(L,IRT)=X(II)                                               IROR0915
  295 NRT=NRATE(L)-1                                                   IROR0920
      DO 300 JIM=1,NRT                                                 IROR0925
      KK=NRATE(L)-JIM                                                  IROR0930
  300 XRATE(L,KK)=RATE(KK)                                             IROR0935
  305 CONTINUE                                                         IROR0940
C                                                                      IROR0945
C  END OF L-LOOP                                                       IROR0950
C                                                                      IROR0955
      IF(LX.EQ.1) GO TO 320                                            IROR0960
      IF (LR.NE.1) GO TO 310                                           IROR0965
```

```
      NRR = NR                                                          IROR0970
      GO TO 325                                                         IROR0975
C                                                                       IROR0980
C  SORT TO FIND LARGEST NRATE(L) WHICH DETERMINES LENGTH OF I-LOOP BELOWIROR0985
C                                                                       IROR0990
  310 KM=LX-1                                                           IROR0995
      DO 315 I1=1,KM                                                    IROR1000
      JJ=LX-I1                                                          IROR1005
      DO 315 J1=1,JJ                                                    IROR1010
      IF(NRATE(J1+1).LE.NRATE(J1))GO TO 315                             IROR1015
      ITEMP=NRATE(J1)                                                   IROR1020
      NRATE(J1)=NRATE(J1+1)                                             IROR1025
      NRATE(J1+1)=ITEMP                                                 IROR1030
  315 CONTINUE                                                          IROR1035
  320 NRR=NRATE(1)                                                      IROR1040
C                                                                       IROR1045
C  WRITE RATE OF RETURN                                                 IROR1050
C                                                                       IROR1055
  325 L1=1                                                              IROR1060
      L2=2                                                              IROR1065
      L3=3                                                              IROR1070
      L4=4                                                              IROR1075
      L5=5                                                              IROR1080
  330 LINE=0                                                            IROR1085
      DO 345 I=1,NRR                                                    IROR1090
      IF(LINE.EQ.0) GO TO 335                                           IROR1095
      IF (LINE.NE.31) GO TO 340                                         IROR1100
  335 WRITE (6,105) (STD(IN),IN=1,18), NO, (A(IN),IN=1,18)              IROR1105
      WRITE (6,120)                                                     IROR1110
      WRITE (6,115)                                                     IROR1115
      WRITE (6,125) LI(1,L1),LI(2,L1),LI(1,L2),LI(2,L2),LI(1,L3),LI(2,L3IROR1120
     1),LI(1,L4),LI(2,L4),LI(1,L5),LI(2,L5)                             IROR1125
  340 WRITE (6,130) XRATE(L1,I),VALIN(L1,I),XRATE(L2,I),VALIN(L2,I),XRATIROR1130
     1E(L3,I),VALIN(L3,I),XRATE(L4,I),VALIN(L4,I),XRATE(L5,I),VALIN(L5,IIROR1135
     2)                                                                 IROR1140
      LINE=LINE+1                                                       IROR1145
  345 CONTINUE                                                          IROR1150
      IF (L5.EQ.20) RETURN                                              IROR1155
      L1=L1+5                                                           IROR1160
      L2=L2+5                                                           IROR1165
```

```
      L3=L3+5                                                          IROR1170
      L4=L4+5                                                          IROR1175
      L5=L5+5                                                          IROR1180
      IF (L1.GT.LX) RETURN                                             IROR1185
      GO TO 330                                                        IROR1190
      END                                                              IROR1195
```

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1969. A computer program for evaluating forestry opportunities under three investment criteria. U.S.D.A. Forest Serv. Res. Pap. PNW-78, 64 pp., illus. Pacific Northwest Forest & Range Experiment Station, Portland, Oregon.

Describes a computer program, written in FORTRAN IV, for evaluating investments by use of criteria of present net worth, benefit-cost ratio, or internal rate of return.

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```
      L3=L3+5                                                    IROR1170
      L4=L4+5                                                    IROR1175
      L5=L5+5                                                    IROR1180
      IF (L1.GT.LX) RETURN                                       IROR1185
      GO TO 330                                                  IROR1190
```

Headquarters for the PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION is in Portland, Oregon. The Station's mission is to provide the scientific knowledge, technology, and alternatives for management, use, and protection of forest, range, and related environments for present and future generations. The area of research encompasses Alaska, Washington, and Oregon, with some projects including California, Hawaii, the Western States, or the Nation. Project headquarters are at:

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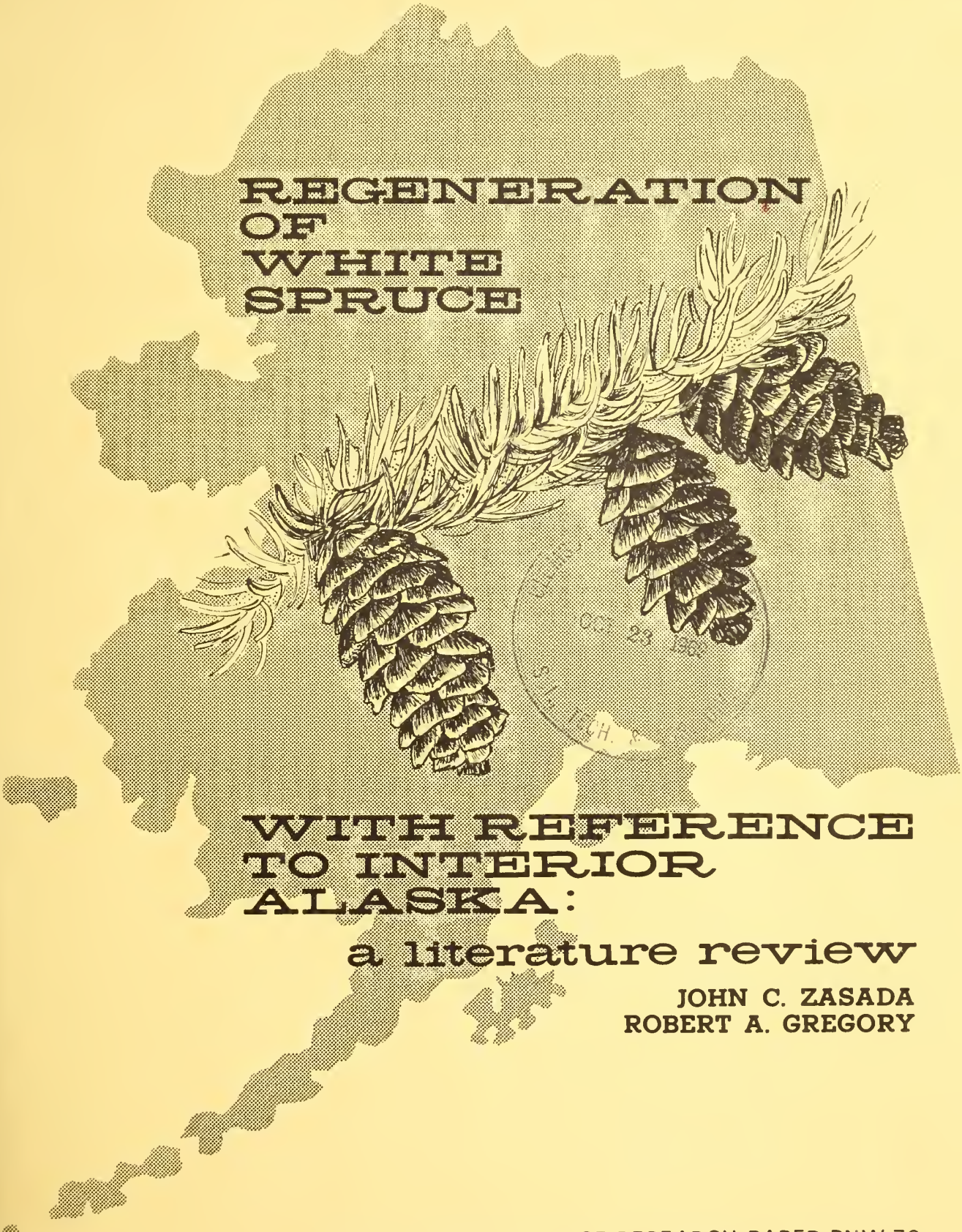

REGENERATION OF WHITE SPRUCE WITH REFERENCE TO INTERIOR ALASKA:

a literature review

JOHN C. ZASADA
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U.S.D.A. FOREST SERVICE RESEARCH PAPER PNW-79

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INTRODUCTION

White spruce (*Picea glauca* (Moench) Voss) has a transcontinental distribution and grows under a great variety of climatic and site conditions (Nienstaedt 1957). In interior Alaska, which embraces all of the area between the Brooks Range on the north and the Coastal Range bordering the Pacific Ocean on the south (Lutz 1956), white spruce reaches the northern limit of its commercial and botanical ranges. It is the major species in the most important forest type in interior Alaska, covering 57 percent (12.8 million acres) of the commercial forest land (Hutchison 1967).

In interior Alaska, white spruce occurs in even-aged stands and attains its best development along the Tanana River and on the south-facing slopes of the Tanana-Yukon upland (Farr 1967). These stands can be pure or they may contain variable percentages of hardwoods. On the river bottom sites in the Tanana area, soils are relatively coarse textured and the parent material is of alluvial origin. The upland soils are finer textured and generally have formed in loess parent material. The soils on both sites are poorly developed and, under mature stands, they are overlain by a thick organic layer. The growth and yield of these stands has been reported by Farr (1967).

As Alaska develops, the value of the white spruce component of the forest resource will increase. Forest managers wish to maintain the level of spruce growing stock; but in Alaska, as elsewhere, the species does not regenerate easily. The difficulty is due, in part, both to natural factors and to those unfavorable economic conditions which limit the possibility for good logging practices and site preparation.

Because of the difficulty of regenerating this species, a great deal of research has been concerned with solving this problem. Most of the literature reviewed reported the results of research conducted in Canada. All of this work will undoubtedly be helpful in development of practices for obtaining natural regeneration in interior Alaska. However, little of this research has actually been conducted in the forested area of the subarctic; and, although the subarctic resembles other portions of the boreal forest, it differs because of the occurrence of permafrost on some sites, exceptionally long hours of summer daylight, the profound effect of topographic position--especially aspect--on growth, and the relatively short growing season. Literature reporting research conducted in northern Europe on Norway spruce (*Picea abies* (L.) Karst. or *P. excelsa* Link) has been incorporated where appropriate. This is particularly true in the section dealing with seed production.

The purpose of this paper is to present the major results and conclusions reported in the literature, and, where possible, include comparable data concerning interior Alaska conditions. It is hoped that this approach will point out some general requirements which must be met in order to obtain natural regeneration of spruce in Alaska.

SEED PRODUCTION

The Seed Production Cycle

White spruce flower buds form the growing season prior to flowering and can usually be distinguished from vegetative buds in late summer (Nienstaedt 1958; Fraser 1962a; Eis 1967a). Microsporogenesis and megasporogenesis occur early the next spring. At St. Paul, Minnesota (about 45° N. lat.), Winton (1964b) reported microsporogenesis beginning on April 22 and 21 of 1961 and 1962, respectively. Pollen dispersal occurred between 19 and 24 days after initiation of meiosis. However, approximately 100 miles north of St. Paul, meiosis began 2 days later in both years with pollen dispersal occurring 26 to 37 days after initiation of meiosis.

Near Ely, Minnesota (about 48° N. lat.), flowering (female strobili) occurred between May 25 and May 30 over a 4-year period (Nienstaedt 1957). Nienstaedt (1958) found bagged female cones were receptive for a period of from 3 to 5 days in northern Wisconsin.

Over a 5-year period, near Ely, initial pollen shedding varied between May 12 and June 1 (Nienstaedt 1957). Near Fairbanks, Alaska (about 65° N. lat.) during 1958, pollen was dispersed during the last few days of May and in early June; in 1962, pollen dispersal began on June 4 and was essentially completed by June 21 with peak activity between June 6 and 12. In 1968, dispersal occurred between May 31 and June 12. Pollen dispersal has been observed as late as July 11 to 12, north of 53° N. latitude (Nienstaedt 1957).

Development of cones, cone scales, and seeds of white spruce was observed in 1964 in north-central Wisconsin (about 45° N. Lat.) by Clausen and Kozlowski (1965). They reported:

> Whole cones, scales and seeds of white spruce...achieved their highest moisture content of the sampling season, ca. 400 percent, in late May or early June. They showed an overall decrease from this time until reaching their lowest point, less than 40 percent, in September.... Actual moisture content increased early in the season in all determinations and then remained constant until August. It decreased during August when cones of white spruce ...had attained their greatest dry weights.

In Connecticut (about 41° N. lat.), controlled pollinations were carried out between May 9 and 16, 1961. Fertilization occurred in early June, rapid differentiation occurred in July, and the embryos were mature by mid-August (Mergen et al. 1965).

Seed maturity, as measured by the occurrence of germination percentages of seed lots collected prior to natural seedfall not appreciably different from germination percentages found at the time of cone opening, occurs before seed dispersal begins. Crossley (1953) reported that seed could be collected in Manitoba (about 51° N. lat. and elevation 4,500 feet) after the second week in August without sacrificing a great deal in seed viability. Seed dispersal began on September 17 in Crossley's study. In a study conducted at Indian Head, Saskatchewan (about 51° N. lat.), Cram and Worden (1957) reported that in one of their study trees the highest germination percentage occurred in seeds collected about 5 weeks before natural seedfall; in another tree, germination

percentage was greatest 1 week prior to seedfall. Cram and Worden found that a cone moisture content (wet weight) of 48 percent and specific gravity of 0.74 are good general indices of seed ripeness.

Near Fairbanks (65° N. lat.) from 1958 to 1962, cones appeared to ripen about August 20 with seed dispersal beginning shortly thereafter. Peak seed dispersal at Riding Mountain Experimental Forest in Manitoba (51° N. lat.), over a 10-year period, varied from late August to early October (Waldron 1965). At Indian Head, Saskatchewan, natural seed dispersal began, on the average, 98 days after pollen dispersal (Cram and Worden 1957).

Although the majority of seed is dispersed during the year of production, some viable seed has been found in cones the next summer (Roe 1946, Rowe 1953b). Crossley (1955) reported that, during a good seed year in the subalpine region of Alberta, about 88 percent of total seedfall occurred in the first month of dispersal; however, seed continued to fall during the winter, early spring, and as late as May. In northern Minnesota, 22 percent had fallen about 1 month after the beginning of dispersal and 87 percent after about 2 months; 6.5 percent fell about mid-November (Roe 1946).

On the basis of the limited data presented above, it appears that, in general, pollen dispersal occurs later in interior Alaska than farther south. However, it also appears that seed maturation and dispersal occur at about the same time over the species range. This indicates a more rapid development of white spruce seed in the subarctic forests. This more rapid development is in line with the findings of Gregory and Wilson (1968) with regard to the formation of the annual ring in white spruce.

Quantity of Seed Produced

An isolated, open-grown, 75-year-old white spruce in northern Minnesota produced an estimated 271,000 viable seeds from 11,874 cones in a good seed year (Roe 1952). During a heavy cone year in southern Ontario, Tripp and Hedlin (1956) reported an average of over 8,000 cones per tree and 92 seeds per cone of which 25 percent or 23 seeds were sound. Nienstaedt (1958) found an average of 28.3 sound seeds per cone in a sample of cones pollinated in bags. A random sample of 180 cones taken from trees near Fairbanks during the excellent 1958 seed year had 60.5 sound seeds per cone. During a year when only a fair crop of cones was produced, there were 11.4 sound seeds per cone, and in two poor cone years, 6.5 sound seeds (Northern Forest Experiment Station 1960-61).

Table 1 summarizes total seedfall at Riding Mountain Experimental Forest, Manitoba (Waldron 1965), and near Fairbanks (Northern Forest Experiment Station 1960-61).

Factors Affecting Seed Production

The annual variation in white spruce cone and seed crops is great. A moderately well stocked, 170-year-old stand near Fairbanks produced one excellent, one fair, and three poor seed crops from 1957 to 1961. At Riding Mountain Experimental Forest, one good, four moderate, two light, and three nil seed crops occurred between 1954 and 1963 (Waldron 1965). Rowe (1955) reported that, over a 40-year period at Duck Mountain and

Table 1.--*Seedfall at Riding Mountain Experimental Forest, Manitoba, and Bonanza Creek Experimental Forest, Alaska*

(Thousand seeds per acre)

Year	Riding Mountain (100-year-old stand)		Fairbanks (170- 180-year-old stand)	
	Total number of seeds	Total number of sound seeds	Total number of seeds	Total number of sound seeds
1957	14	5	138	86
1958	10	2	16,512	10,733
1959	324	133	123	27
1960	5,625	3,319	--	--
1961	1,409	1,000	--	--

Porcupine Mountain Forest Reserves (about 52° N. lat.) in Manitoba, 12 heavy cone crops occurred. A 30-year record of seed production in southern Finland (about 62° N. lat.) showed that truly good Norway spruce seed years occurred with regularity at the infrequent interval of 12 to 13 years (Sarvas 1957). Uskov (1962) reported abundant seed years in Norway spruce at 3- to 5-year intervals in the northern part of the Vologda Region in Russia (about 60° N. lat.). To understand this variability and how seed production might be increased, one must acquire some knowledge of the factors influencing production.

AGE OF TREES AND STANDS

Cones have been observed on trees as young as 10 years old,[1/] and viable seeds have been obtained from a 13-year-old tree in Maine.[2/] Nienstaedt (1957) mentioned the occurrence of excellent seed crops on 20-year-old, plantation-grown spruce. Stiell (1955) found cones on 20-year-old plantation trees in Ontario and observed that the proportion of cone-bearing trees was greater in more widely spaced stands. He stated that, by age 30 years, 86 percent of the trees in 7- by 7-foot spacing and 42 percent in 4 by 4 spacing were bearing cones. Studies in the mixed-wood forests in Manitoba and Saskatchewan indicated that the beginning of spruce seed production in natural stands occurred at 45 to 60 years of age (Rowe 1955). In Alaska, good cone crops have been observed for trees of this age (45 to 60 years) and for individual trees and stands up to 170 years old.

In general, it appears that, under natural conditions, attainment of a certain minimum crown size and age determines the inception and quantity of flower and seed production in trees (Matthews 1963). Kramer and Kozlowski (1960) stated that most trees produce seed in greatest quantities during middle age, after the

1/ Personal correspondence with Mr. Z. A. Zasada.

2/ Personal correspondence with Mr. A. C. Hart.

period of more rapid height growth has occurred.

WEATHER

Weather at the time of (1) bud setting, (2) flowering, and (3) seed maturation affects seed production and each will be considered below.

Bud Set

Tiren (1935), working with Norway spruce in Scandinavia, concluded that above-average temperatures during June to mid-July of the year of flower bud formation produced high seed yields. A study by Fraser (1958) of the factors influencing spruce flowering in Ontario indicated that hot, dry summers favor flower primordia initiation. In Ontario, MacLean (1959) showed a relationship between seed crops and early spring temperatures of the preceding year; high temperatures were associated with better seed crops. Uskov (1962) reported a significant statistical relationship between the fruiting of spruce stands and the weather (i.e., temperature, precipitation, relative air humidity, and cloudiness) during May, June, and July of the previous year in the northern part of the Vologda Region. The excellent seed year of 1958 in interior Alaska was preceded by an exceptionally hot, dry summer. In correlating weather with seed production of Norway spruce, Sarvas (1957) also observed a favorable effect of abnormally warm or dry seasons seasons, but there were numerous exceptions during the period 1900-55. He emphasized the frequent occurrence of exceptionally high summer temperatures associated with drought, without any subsequent abundant flowering of spruce.

Flowering and Seed Maturation

Concerning weather and flowering, Andersson (1965) stated:

> ...one finds only few data in the literature concerning the effect of the climate and of climatic variations upon the development of floral buds (the meiotic divisions of the micro- and mega-spore mother cells, pollen mitosis and the continued development of the female gametophyte)...

The observation of these phenomena requires exacting techniques and this, perhaps, is one of the reasons for the lack of this information.

The effect of weather on flowering must be considered at least as important as the effect of weather on the formation of reproductive buds. This may be particularly true in subarctic regions. Here, weather conditions at the time of pollen and female gametophyte formation (early to mid-May) may be unfavorable; conditions prevailing at the time of bud formation may be more optimal in any given year. Uskov (1962) stated that a seed crop can be completely destroyed if the frosts are severe enough. He concluded that seed crop periodicity in the northern part of the Vologda Region is often affected by late frosts.

For pine, "A good flowering year is as a rule (though not always) followed by a rich cone crop in the following year but a rich cone year is not always a good seed year" (Andersson 1965). This may also apply to spruce except that the year of flowering and seed dispersal are the same. Destruction of seed during the period of maturation could result from a number of factors. Insect destruction of seed may be of prime importance; however, the effect of adverse weather on seed maturation may also be important. The latter factor has received little attention in the study of white spruce seed production.

POLLINATION

The extent of successful pollination of female ovules is an important factor in determining the quality of white spruce seed crops. Sarvas (1955, 1957) concluded that the high number of empty Norway spruce seed is usually the principal factor reducing seed quality in southern Finland. This is due mainly to incomplete pollination, although some empty seed will occur in spite of sufficient pollination. Nienstaedt (1958) reported that no filled seed developed in unpollinated cones. Both Sarvas (1955, 1957) and Hagner (1958) observed that pollination of spruce flowers remained, as a rule, lower during years when flowering was poor. Nekrasov (1961) reported that supplementary pollination of *P. glauca* produced 49 percent sound seed, whereas naturally pollinated controls gave 12 percent. Navasajtis (1966) stressed the importance of cross-pollination to seed production in white spruce. Mergen et al. (1965) reported that 60 percent of the seed produced in cross-fertilized cones were sound, whereas only 13 percent produced by self-fertilized cones were sound. They found no barrier to self-pollination or self-fertilization; however, self-fertilization often resulted in embryo collapse.

Rain, which created conditions unfavorable for pollination during the period of maximum pollen flight, was the main reason observed by Nienstaedt (1958) for failure of a potentially heavy seed crop of white spruce in northern Wisconsin. Sarvas (1955) stated that during 5 years of observations in southern Finland, rain often delayed the start of flowering or interrupted the spread of pollen for a time, but as a rule its influence was not enough to ruin a potentially good seed year. Wind, stand conditions, and the effect of weather on pollen formation are also important factors in determining the quantity of pollen available for pollination.

LATITUDE AND ELEVATION

Data on the effects of latitude and elevation on the production of white spruce seed were not found. However, this aspect of Norway spruce seed production has received attention in Finland (Sarvas 1957), Sweden (Hagner 1958; Andersson 1965), Bulgaria (Velkov 1965), and Russia (Norin 1958).

In Sweden and Finland, Norway spruce seed production in the north is considerably less than that in the south. Sarvas (1957) has calculated that in the northernmost spruce stands, the seed crops are only about 1 percent as good as the best in central Europe. Hagner (1958) has also observed that spruce cone production declines with increasing elevation; the yield of cones in northern Sweden at 550 meters is about 55 percent of that of 50 meters. Sarvas (1957), Hagner (1958), and Velkov, et al (1965) also found that the number and size of spruce cones and the number of seeds per cone decrease with latitude and elevation. Yet, even at the northern timberline in Finland, filled seed percentage may exceed 70 percent in good seed years. The 1958 white spruce seed crop in Alaska appears to compare very favorably with the number of seeds produced in good seed years in southern parts of the species range (see table 1).

Clark (1961) mentioned extremely slow growth of dwarf trees near the altitudinal and latitudinal tree limits to illustrate a situation where food synthesis appears to barely balance respiratory loss. Simple life functions, such as needle replacement, probably used most of the surplus photosynthate, leaving little for seed production. It seems reasonable to suspect lower seed production at high latitudes and elevations or wherever food synthesis is limited. In fact, a seed-production and seed-quality limit, as well as a vegetation limit, has been observed to exist (Andersson 1965).

Seed Losses

White spruce seed crops are subject to enormous losses before seedfall occurs. A brief discussion of the biological factors important in cone and seed destruction is given below.

INSECTS

Tripp and Hedlin (1956) divided insects that feed on white spruce cones into two groups: (1) "the internals," or those that occupy a restricted environment, with each individual passing its entire feeding period within a single cone; and (2) "the casuals," or those that are not restricted to a single cone, such as some foliage feeders that may also feed on cones. They found the following internal insects in samples of cones from Ontario and Saskatchewan:

Laspeyresia youngana (Kft.)
Pegohylemyia anthracina (Czerny)

Three species of Cecidomyiidae identified as:

Dasyneura canadensis Felt
D. Rachiphaga Tripp
Phytophaga carpophaga Tripp
Megastigmus piceae Rohwer
Two unidentified species of Cecidomyiidae

Among the casual species observed in Ontario and Saskatchewan were:

Dioryctria reniculella (Grote)
D. abietella (D. & S.)
Choristoneura fumiferana (Clem.)
Polychrosis piceana Freeman
Eupithecia togata mutata Pears.

On occasion the casuals are believed to destroy large quantities of cones or seed, but this type of loss is sporadic and difficult to record.

Tripp and Hedlin (1956) concluded that in the vicinity of Ottawa, Canada, the internal insects have been responsible for the destruction of about 28 to 53 percent of the potentially sound seed, depending on the size of the cone crop. During good seed years, the insects become widely dispersed, leaving a large percentage of the cones uninfested; but in light seed years, multiple insect infestations plus many empty seeds result in few or no sound seeds. *Laspeyresia youngana* and *Pegohylemyia anthracina*, may destroy up to 33 and 60 percent, respectively, of the seed crop.

In the vicinity of Anchorage and Fairbanks, Alaska, McCambridge (1957) found *Laspeyresia* spp., Cecidomyiids, and *Megastigmus piceae* in white spruce cones produced in 1954. In a study conducted from 1958 to 1962, in a 300-mile radius of Fairbanks, Werner (1964) found the following cone and seed insects: *L. youngana, M. piceae, Dasyneura canadensis, D. rachiphaga, Phytophaga carpophaga,* and *Pegohylemyia*. He reported,

> Insects damaged 3 - 6% of the seeds per cone during 4 of the 5 years of the study. In 1962, damage increased to 50% and most of it was caused by *Pegohylemia* [sic] sp. Both cone and seed damage was least in 1958 when there was an abundant cone crop and the number of seeds per cone was high. In contrast, the greatest insect damage was in 1962 when few cones were produced but the number of seeds per cone was high.

In northern Wisconsin, Nienstaedt (1957) found only 3.3 percent of the cones bagged during pollination were damaged by insects. Insects damaged 56.5 percent of unprotected, open-pollinated cones.

An extended diapause, according to Tripp and Hedlin (1956), is a characteristic common to many white spruce cone insects. No *Laspeyresia* larvae remained in diapause during a good cone year, but about 40 percent did so when cones were scarce. Thus, year-to-year cone crop variation does not appear to seriously affect survival of cone insects.

DISEASE

Only one disease, the rust, *Chrysomyxa pirolata*, is reported to occur on white spruce cones (Nienstaedt 1957). This rust has been observed on white spruce cones in Alaska by Kimmey and Stevenson (1957). A species of *Chrysomyxa*, probably *C. pirolata*, was very abundant on white spruce over an extensive area south of the Alaska Range in 1960.[3/] During 1968, this rust was present in all stands observed near Fairbanks (north of the Alaska Range).[4/]

Infected cones are said to produce no seed. In 1960, an attempt to collect sound seed from south of the Alaska Range was made difficult because of the high incidence of infected cones. Despite abundant cones, apparently few sound seeds were produced.

SMALL MAMMALS

Red squirrels (*Tamiasciurus hudsonicus*) are common in Alaska and occur over most of the boreal forest region of North America. In Alaska, coniferous seed is an important part of their diet (Brink;[5/] Brink and Dean 1966; Smith;[6/] Streubel[7/]). Captive red squirrels consumed 144 cones per day and can thrive on a white spruce seed diet, but under natural conditions their diets are supplemented with other foods. In captivity, these squirrels preferred white spruce to black spruce (*Picea mariana* (Mill.) B.S.P.) cones (Brink and Dean 1966).

Smith (see footnote 6) has reported that red squirrels are able to thrive on a diet of white spruce buds. During years of cone crop failure, their winter diet may be restricted to buds, which could mean a reduction in the number of potential cones and seeds for the next year.

That squirrels can be considered major consumers of white spruce cones and seed is evidenced by the frequent occurrence of large cone caches (Rowe 1955; Lutz 1956; Wagg 1964a; Streubel, see footnote 7). Streubel reported that, depending on the daily cone consumption rate used in his calculations, squirrels harvested 10 to 69 percent of the cone crop during 1967. He also reported cone caches containing as many as 14,000 cones. During 1957, most of the cones produced during this medium cone year had been harvested by squirrels by the beginning of seed dispersal time.

Red squirrels' cone caches can be a source of seed for silvicultural purposes (Wagg 1964a). However, during the process of cone stripping and seed consumption, squirrels probably scattered little viable seed (Brink and Dean 1966), and they are likely not important as seed dispersal agents.

Artificial Stimulation of Seed Production

Kramer and Kozlowski (1960) stated that a relatively high concentration of carbohydrates appeared to be necessary for the initiation of

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3/ Identification by T. W. Childs, Forest Pathologist, Pacific Northwest Forest and Range Experiment Station.

4/ Identification by Dr. R. G. Krebill, Forest Pathologist, Intermountain Forest and Range Experiment Station.

5/ Brink, C. H. Spruce seed as a food of the squirrels *Tamiasciurus hudsonicus* and *Glaucomys sabrinus* in interior Alaska. 1964. (Unpublished master's thesis on file at Univ. Alaska, College.)

6/ Smith, M. C. Red squirrel (*Tamiasciurus hudsonicus*) ecology during spruce cone failure in Alaska. 1967. (Unpublished master's thesis on file at Univ. Alaska, College.)

7/ Streubel, D. P. Food storing and related behavior of red squirrels (*Tamiasciurus hudsonicus*) in interior Alaska. 1968. (Unpublished master's thesis on file at Univ. Alaska, College.)

flower buds in forest trees. Numerous methods of stimulating seed production, such as girdling, thinning, and soil fertilization, are aimed at increasing food supply. Girdling restricts downward movement of photosynthates so that food supplies become more abundant in the flower-producing parts of the tree. Thinning and fertilization affect the external factors of temperature, light, soil water, and nutrition; and these, in turn, influence the rates of photosynthesis and carbohydrate accumulation.

Holst (1959) reported that a combination of root pruning, drought, fertilization, and lowering of the auxin level with short-day treatments and antiauxins promoted flowering in white spruce. He also found that white spruce in the ready-to-flower stage can be root-pruned, fertilized with NH_4NO_3, and girdled with good effect. Increased seed yields in other species as a result of thinning, release, fertilization, and other practices indicate that further work in this area may prove valuable in increase of white spruce seed production in selected stands (Matthews 1963).

Seed Crop Prediction

Basically, seed crop prediction aims to provide an accurate estimate of the quantity of seed likely to be produced as early in the production cycle as possible. A sound method of prediction would provide information on which seed collection programs and seedbed preparation could be scheduled to take advantage of seed. Two possible methods of prediction suggested in the literature are discussed below.

Eis (1967a) concluded that a method of prediction based on the abundance of male and female reproductive buds could be developed and would be a useful means of prediction. Early forecasting of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Silen 1967) and western larch (*Larix occidentalis* Nutt.) (Roe 1966) seed crops based on the abundance of reproductive buds has been described. Predictions based solely on the abundance of reproductive buds are of limited use as these observations only indicate the potential which exists under optimal conditions for a good seed year. Observation of cone and seed development subsequent to flowering and fertilization would also be necessary to refine the prediction.

The reported relationship between climatic variables and seed production reported may also be of predictive value. Uskov (1962) has suggested the use of this relationship in predicting Norway spruce seed crops. The relative simplicity of this system makes it attractive. However, reliable data on seed crops from many stands or from individual stands for many years and weather conditions at the time of reproductive bud formation, flowering, pollination, and seed formation are a prerequisite. These data are not available for interior Alaska.

At present, the method of seed crop assessment for white spruce in interior Alaska is based on the presence of mature cones and actual seedfall. No prediction criteria have been developed for interior Alaska.

GERMINATION, INITIAL SURVIVAL, AND SEEDLING ESTABLISHMENT

Germination, early survival, and seedling establishment are three critical periods in the life of a developing seedling. Germination and early survival will be considered jointly in the following discussion because this is commonly found in the literature and because the later stages of germination and initial survival are affected similarly by the same

environmental factors. The period of establishment begins after the seedling has hardened off; however, the period of initial survival is often considered as lasting until the end of the first growing season. Establishment is generally considered as requiring three to five growing seasons after germination, varying with site and seedbed conditions.

Germination and Initial Survival

White spruce germination is epigeal. That is, the primary root elongates first and grows into the soil; the hypocotyl arches upward, pulling the cotyledons into the air where they expand into photosynthetic organs. The seedcoat is shed during this process and the plumule produces a stem bearing leaves (Kramer and Kozlowski 1960).

Seedling shoot and root elongation during the first growing season has been reported by Rowe (1955), Place (1955), Day (1963), Eis (1965) and others. Eis found that, among surviving seedlings, root length averaged 24 millimeters at the end of germination and 52 millimeters at the end of the first growing season; shoot length was 10 and 14 millimeters, respectively. These values will vary with site and weather conditions, but they do give some idea of the size attained by the seedling during the first growing season.

Field germination on mineral soil generally occurs in June and July. For example, at Riding Mountain Experimental Area very little germination occurred in May and the majority (75 percent) in June (Waldron 1966). On 24 mineral soil seedbed plots at Bonanza Creek Experimental Forest (near Fairbanks), 1,300 white spruce seedlings germinated between June 1 and September 1, 1968. Of these, 1,100 (about 85 percent) germinated on or before June 24.

The newly germinated seedling is most susceptible to heat injury during the first growing season and prior to hardening of the hypocotyl when the outer stem tissues die and become dry and straw colored (Smith 1962). This process is caused by the development of the cork cambium. In Douglas-fir, the formation of this lateral meristem may be the most important single development that affects heat resistance (Smith 1958). This tissue develops when the Douglas-fir seedling is 6 or 7 weeks old. No similar data were found for white spruce.

FACTORS AFFECTING GERMINATION AND INITIAL SURVIVAL

Before the specific effects of different seedbeds on germination and initial survival are considered, some general information concerning the effects of temperature, water, and light will be presented. These data, although mostly derived from laboratory tests, indicate why different seedbeds vary in their effect on white spruce seeds and newly germinated seedlings. It must also be stated that the reason for the apparent stress on germination in the subsequent discussion is that the majority of information available pertains to this phase of regeneration and not because it is the most important per se. In fact, as Rowe (1955) stated, the problem of regeneration may not be one of germination as much as of seedling survival.

The seed of white spruce is characterized by embryo dormancy which may be broken by storage in moist sand at 40° F. for 60 to 90 days (U.S. Forest Service 1948), cold-soaking for 20 days at 34° to 38° F. (Crossley and

Skov 1951), or warm-soaking for 24 hours at 70° F. (Wagg 1964b). MacGillivray (1955) found no significant difference in white spruce germination between cold-stratified seed stored for 3 and 14 months. Hellum (1968) reported that cold-stratification adversely influenced germination of the three lots of seed he tested. Heit (1961, 1968) reported that complete germination can also be obtained without pretreatment when light, temperature, and moisture conditions are properly controlled. White spruce seeds have germinated at 35° F. after 1 year or more of stratification (MacArthur and Fraser 1963). Heit (1949) has reported that, in the laboratory, the seed of white spruce did not germinate promptly and completely at temperatures of 68° F. or below. Carmichael (1958) found that the rate of germination of white spruce seed was unchanged by exposure of up to 70 hours at 120° F. and relative humidities (R.H.) up to 30 percent. There was a small reduction at 150° F. and 10 percent R.H. and a great reduction at 20 and 30 percent R.H. A temperature of 180° F. was lethal under all circumstances.

Under field conditions, Rowe (1955) observed a mean air temperature of 44° F. during the week before the first seedlings appeared and a mean of 57° F. during the week in which they formed.

Thiourea substituted for cold treatment in *Picea* sp. (Mayer and Poljakoff-Mayber 1963). Soaking white spruce seed in several concentrations of the potassium salt of gibberellic acid had no effect on its rate of or percent of germination (Grover 1962). Timonin (1966) reported that exposure to ultrasound for 1, 2, or 4 minutes greatly improved the rate of and percent of germination; 6 minutes' exposure was lethal. Vaartaja (1963) found that germination was not affected by extreme pH. Surface sterilization of seed resulted in a significant reduction in germination of white spruce seedlings (Timonin 1964).

Data on temperature optima for seedling growth after germination were not found in the literature. High temperatures can cause seedling mortality by desiccation or by being directly lethal to the seedling. Lethal temperatures may vary to some extent with seedling turgidity but are generally in the 122° to 140° F. range. In moist soil, they may be as high as 158° F. (Day 1963).

Soil water and, in some cases, free water at the soil surface are important to germination and early survival. The first process during germination is the imbibition of water by the seed (Mayer and Poljakoff-Mayber 1963). Waldron and Cayford (1967) reported that germination began at a seed moisture content of 30 percent; at 50 percent, more seed germinated than did not germinate; and at 80 percent moisture content, all seeds germinated. Complete saturation may reduce germination.

Soil water is important to the germinating and developing seedling because it maintains turgidity of the cells and allows metabolic processes to function at rates which insure rapid root penetration to a relatively stable water supply and production of adequate foliage. As mentioned above, turgidity may also be important in determining the susceptibility of the seedling to direct effects of heat.

The importance of light to initial survival is obvious. However, it can also be detrimental when it results in high temperatures and high transpiration rates. The role of light intensity or quality in germination is less obvious. Light treatment of white spruce is beneficial (Jones 1961) and Heit (1968) classifies white spruce as a species requiring light for germination. Sarvas (1950) reported that the seed of Norway spruce germinated much more quickly in light

than in darkness; however, the final result (i.e., percent of germination) was the same. More information is required on this aspect of germination as well as all aspects of the effect of environmental factors on germination and initial seedling survival in white spruce.

Burgar (1964) reported differences between small and large seeds in such factors as total germination, percentage of live seedlings produced, and seedling height at the end of 100 days. Hellum (1966) found a positive relationship between seed weight and both cotyledon number and hypocotyl length. However, he also stated that adverse site conditions may eliminate the influence of seed size on the size of the germinant.

Organic Seedbeds

Raw humus.--Numerous studies have shown that surface organic layers, particularly the thick unincorporated organic layers common to northern coniferous forest regions, are generally very poor or at best, intermediate quality, white spruce seedbeds when compared with other types (e.g., LeBarron 1945; Phelps 1948; Crossley 1952a, 1955b; Parker 1952; Blyth 1955; Place 1955; Quaite 1956; Davis and Hart 1961; Lees 1963; Prochnau 1963; Glew 1963; Wagg 1964a; Eis 1965; Waldron 1966; Jarvis et al. 1966; Hughes 1967). In New Brunswick, Place (1955) found that organic matter accumulations of greater than 2 inches may prevent seedling establishment. Waldron (1966) reported that the effects of organic matter on germination will depend on the depth of the material; on exposed sites, a thin layer of litter may increase germination in dry years. In most cases, one of the major obstacles to successful establishment of white spruce reproduction is the predominance of a raw humus seedbed type.

In reference to soil organic layers, Hawley and Smith (1954) stated:

> ...when kept moist this material makes an excellent medium for germination of most species. The main difficulty is that even in shaded situations it remains moist only when deluged by frequent rains, under the influence of direct sunlight it dries out very rapidly.

Furthermore, increased insolation causes high temperatures at the surface of the organic layer, which is a poor conductor. Eis (1965) recorded temperatures as high as 135° F. and Day (1963) as high as 185° F. Temperatures of this magnitude would be lethal to spruce seedlings.

Rotted wood.--Spruce seedlings often become established in rotting wood; i.e., wood which is well decayed, yet compact (Decie and Fraser 1960). Rowe (1955) stated that, in the absence of any drastic disturbance of the humus layer, rotted wood is the favored surface medium in most stands in the Mixedwood Section of Saskatchewan. Wagg (1964a) and Eis (1965) have also reported the advantage or desirability of rotted wood over humus. Place (1950) showed that the moisture regime of rotted wood is stable and adequate for seedling establishment. On logs and stumps, seedlings are well above the forest floor where they are safe from covering by leaves and, because few other species grow in the medium, they are free from competition (Rowe 1955). Other advantages cited by Rowe are:

1. Improved light conditions--stumps are generally beneath openings in the canopy;
2. Improved temperature conditions--logs and stumps show higher temperatures than the germination layer of the adjacent soils;
3. Less danger of damping off on these seedbeds, and mycorrhizal development is better.

Available evidence indicates how white spruce seedlings, rooted in rotted wood beneath forest stands, are affected by the removal of the forest canopy. Wagg (1964b) stated that, in the Peace and Slave River lowlands, rotted wood may be an important seedbed under stands. But, in clearcuts, the increased temperature and the more rapid drying rate of rotted wood limit seedling establishment. In the subalpine forests of Alberta, hybrid spruce (*Picea engelmannii* X *glauca*) exhibited less mortality on shaded, decayed wood than on a mineral soil seedbed of sandy loam texture (Day 1963). Candy (1951) found excellent coniferous reproduction, which had become established prior to logging, growing on rotted wood in logged areas in the eastern boreal regions of Canada. Moisture conditions are more favorable, however, in eastern than in western boreal regions; and, as pointed out by Candy, this type of reproduction was much less abundant west of Lake Superior.

An interesting role played by rotted wood in white spruce regeneration in the boreal forests of the large river lowlands of western Canada has been reported (Wagg 1964b). Under mature stands, and in the absence of mineral soil, seedlings may become rooted on rotted wood. Alluvium deposited during flooding, which is not detrimental to the seedlings, buries a portion of the seedling's stem and creates conditions under which white spruce is known to form adventitious roots. The alluvium, which is not as susceptible to drying as rotted wood when exposed by overstory removal, assures a more stable source of soil water. This sequence of root development may also be important in similar areas of interior Alaska.

Moss.--Moss seedbeds are common under undisturbed and logged areas in the boreal forest. Generally speaking, this type of seedbed may be favorable for germination early in the growing season, but subsequent survival is poor because of excessive drying. Smith (1962) stated that living mosses can be favorable or unfavorable, depending on whether they grow faster or slower than new seedlings. Johnston[8/] reported that black spruce seedlings are often killed by rapidly growing moss.

Place (1955) has reported the effect of different moss species on the germination and survival of spruce and other coniferous species in southern New Brunswick. The following discussion summarizes Place's findings, which may be applicable to interior Alaska.

During wet years, sphagnum moss, on moist but not boggy sites, is not a desirable seedbed. However, during dry years, when adjoining seedbeds are too dry for germination or seedling survival, sphagnum provides an almost ideal seedbed because of its moisture retention characteristics and good aeration.

Polytrichum commune, when growing in low, open stands on dry, sandy soils, creates favorable germination conditions. Dense growths of this species are unfavorable because of low light intensity and because the thick fibrous layer formed by the dead moss prevents the seedling roots from reaching a stable water and nutrient supply. High temperatures and moisture stress, both causes of seedling mortality, are also common under these conditions.

Dicranum rugosum was found to be a moderately favorable seedbed. This species can modify the moisture conditions of its own environment, thus creating relatively favorable conditions for germination and

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8/ Johnston, W. F. Effect of vegetation and surface condition on artificial reproduction of black spruce in a deforested swamp in north-central Minnesota. 1967. (Unpublished Ph.D. thesis on file at Univ. Mich., Ann Arbor.)

survival. Extreme drying and subsequent high temperatures are not as common with this species as in dense growths of *P. commune*.

Calliergonella (or *Pleurozium*) *schreberi* is generally a poor seedbed for spruce. The species cannot endure direct sunlight and attendant conditions during the summer and usually dies and disappears after logging opens the canopy. Seedlings growing on this seedbed would also suffer mortality. Of the moss species studied by Place, this species provided the poorest seedbed conditions. However, it was more suitable than bare litter. *Hylocomium splendens*, another member of the feather moss group (as is *C. schreberi*), has a similar, or perhaps even more detrimental, effect on spruce regeneration.

Place concluded that the effect of most moss species on regeneration is variable and that the effect of a given species depends a great deal on where it is growing and the density of the moss stand.

Mineral Soil Seedbeds

The majority of data reported in the literature indicated that exposed mineral soil is the most favorable seedbed for germination and early survival of spruce (LeBarron 1945; Phelps 1949, 1951; Parker 1952; Crossley 1952a, 1955a, 1955b; Blyth 1955; Place 1955; Quaite 1956; Ackerman 1957; Weetman 1958; MacLean 1959; British Columbia Forest Service 1961; Davis and Hart 1961; Prochnau 1963; Wagg 1964b; Glew 1963; Jarvis 1966; Eis 1965, 1967a; Jarvis et al. 1966; Scott 1966; Waldron 1966; Hughes 1967; Arlidge 1967). This type of seedbed most closely approximates conditions of a stable, adequate moisture supply, favorable temperatures, and sufficient nutrients. The nature and the arrangement of soil particles also favors intimate contact between the soil water films and the seed.

Although mineral soil is the most favorable seedbed, some detrimental effects have been reported. Heavy soils may become crusted and fissured (MacLean 1959) or baked upon exposure (Gilmour and Konishi 1965). They are also subject to frost heaving (Place 1955). Sandy to sandy loam soils may be too dry for germination in the open (Place 1955; Day 1963). Impairment of physical properties by compaction and reduction of porosity may greatly reduce seedling growth (Weetman 1958). Growth may also be poor on leached A_2 horizons (Place 1955).

Shade

Shade produced by living or dead objects may increase germination and early survival by reducing surface temperatures and evapotranspiration. Day (1963) reported that 40 percent shade reduced mortality in hybrid spruce on all seedbed types tested. In British Columbia, conditions for germination were better under shade; in undisturbed humus, the only seedlings which survived were in the shade of rocks and logs or rooted in rotted wood (Eis 1965). Glew (1963) found the majority of stocked quadrats he observed were not exposed to direct light. Blyth (1955), Place (1955), Prochnau (1963), and others have also reported improved germination and early survival under some degree of shade. Whether shade is produced by living plants or dead objects will only be important if the living plants are also competing with the seedlings for soil, water, and nutrients.

Seedling Establishment

Most white spruce seedling mortality occurs during the first 3 to 5 years after germination (Quaite 1956; Haig 1959; Canada Department of Northern Affairs and Natural Resources 1960;

Prochnau 1963; Eis 1967b). This is generally the period of seedling establishment.

FACTORS AFFECTING SEEDLING ESTABLISHMENT

Seedling establishment is affected by the same factors influencing germination and initial survival as well as by other factors. In some cases, however, the conditions optimal for germination and initial survival may not be the most favorable for seedling establishment and growth. For example, Prochnau (1963) reported that, in general, initial survival was best on mineral soil seedbeds; however, seedling height growth was best on mixed (mineral soil-humus) seedbeds. Although germination is good on rotted wood, seedling growth is extremely slow (Rowe 1955). For example, 20 to 30 years was required for seedlings to reach breast height on rotted wood whereas, on mineral soil, 10 to 15 years was a common age for reaching this height (Rowe 1955). Finally, germination and initial survival are favored by more shade than is optimum for seedling growth. These differences are directly related to the anatomical and physiological changes which occur during seedling development and to the more varied environmental conditions through which the seedling must survive.

The most important factors affecting seedling establishment are soil moisture, light, and nutrient availability and how these are affected by competing vegetation. Other factors which may become important during this period are soil heaving, leaf smothering, and animal and insect damage.

Soil Water and Nutrients

Biotic and abiotic variables are the two sets of factors affecting soil water availability. The abiotic factors consist of the dominating influence of rainfall patterns, physiography, soil, and site. Interior Alaska and the western portion of the boreal forest are characterized by low annual precipitation; in many areas, this is less than 20 inches. Soil water deficits are probably common during the growing season even though this is a relatively wet period of the year. Even on favorable sites, drought may cause some seedling mortality during normal years and excessive mortality during dry years.

Lutz and Caporaso (1958) listed two general site categories in Alaska on which commercial spruce stands do not occur or on which white spruce is absent. Poor tree-soil water relations are among the edaphic variables which limit the growth of spruce on these sites. One of these categories is characterized by a shortage of available soil water. These areas include, among others, oversteepened slopes with south and west exposures and gentler south and west slopes with coarse-textured soils. These areas have probably never supported white spruce.

The second general group of sites is characterized by permafrost near the surface. Attendant with the occurrence of permafrost are such factors as impeded internal drainage, poor soil aeration, and low soil temperatures. All of these factors inhibit root growth. Permafrost occurs most commonly on north slopes and, in these situations, open stands of black spruce predominate.

Permafrost also occurs on potentially productive sites; e.g., in overmature spruce stands in the Chena and Tanana River valleys.[9/] It is in these areas that permafrost may complicate white spruce regeneration.

9/ Dr. L. A. Viereck, personal communication.

Although no research has been conducted concerning the effect of permafrost on regeneration on these sites, it can be concluded from the above-mentioned factors that its effect would probably be detrimental. Extensive disturbance or destruction of the moss layer will be required on these sites to raise soil temperatures, causing the permafrost to recede.

The influence of competing vegetation, the main biotic factor, is superimposed on the abiotic factors. During the period of seedling establishment, the root density of competing vegetation in the surface 10 to 12 inches of soil is critical.

Nutrient supply is extremely important. To date, no work has been completed in Alaska on the relationship between soil fertility and white spruce growth. Field observations indicate that, in some areas, this may be a limiting factor to growth but it may not be as critical during establishment.

Light

Light affects seedling establishment in several ways. First, enough light must be available so that the amount of photosynthate produced is adequate to fulfill normal respiration and minimal growth requirements. If this is not the case, mortality will occur. Too much direct radiation, on the other hand, may limit growth by causing drought.

White spruce is generally categorized as relatively shade tolerant. Place (1955) reported that light intensities below 20 percent of full sunlight can be considered limiting. Eis (1967) found that the rate of height growth of young seedlings under 60 percent of sunlight was twice as great as under 20 percent of light. Intensities greater than 60 percent increased height growth only slightly but did result in better diameter growth. Quaite (1956) observed that seedlings were much more vigorous on scarified plots beneath a partially cut stand than beneath a dense undisturbed stand. This may have been due to greater water availability as well as light intensity differences. High shade--i.e., that produced by a shelterwood overstory--may be less detrimental than low shade--that produced by herbaceous and low, woody vegetation. However, this effect may be related to competition for water and nutrients, too.

Competition

Spruce establishment is hampered by herbaceous and woody species (e.g., Blyth 1955, Crossley 1955a, Rowe 1955, Ackerman 1957, Waldron 1966). This is due to competition for soil water, light, and nutrients. The reproductive characteristics of the competing species and the ecological tolerances of these species, relative to white spruce, are important factors affecting the development and nature of this competition.

Most herbaceous and woody angiosperms reproduce prolifically by suckering or sprouting after the death of the main stem. The sprouts or suckers are able to utilize the parent plant's root system for water absorption and the food reserves stored before death. Vegetative reproduction is common to both birch (*Betula papyrifera* Marsh.) and aspen (*Populus tremuloides* Michx.) but not white spruce. To survive, the spruce seedling must develop its own root system, and it is dependent on stored food reserves in the seed and photosynthate produced by the cotyledons and first needles.

Even when reproduction of all species is accomplished by seed, spruce may be at a disadvantage. For example, good seed years for birch are probably more frequent than for spruce. Seed dispersal for birch is also probably more efficient than for spruce because the seed is lighter.

Most herbaceous plants are also prolific seed producers and are capable of rapid establishment and growth in disturbed areas.

Seedling tolerance of environmental conditions is also important in determining which species will flourish. White spruce is more tolerant than birch or aspen to low light intensities, but does not grow as rapidly as these two hardwood species at high light intensities. Jarvis and Jarvis (1963a) have reported that the growth of Norway spruce was more sensitive to both wet and dry soil than was the growth of European species of birch (*B. verrucosa* Ehrh.) and aspen (*P. tremula* L.). That is, spruce growth under these conditions was reduced relatively more than was the growth of birch or aspen. However, spruce seedlings were the most drought resistant (Jarvis and Jarvis 1963b). Whether these relationships apply to the species of spruce, birch, and aspen in Alaska, at comparable stages of development, is not known. Lutz and Caporaso (1958) have reported that aspen is the most tolerant of interior Alaska species to dry site conditions, and that only white spruce approached it in this respect.

Other Factors

Soil heaving.--Soil heaving on mineral soil seedbeds can cause considerable mortality to seedlings during the period of establishment. The roots are near the surface and soil movement caused by freezing of soil water may damage them mechanically or expose them. Parker (1952) and Place (1955) have reported that this phenomena is most severe on fine-textured and wet soils. Crossley (1955a) found that soil heaving is unimportant as a cause of mortality on scarified seedbeds after seedlings are 3 years old. Rowe (1955) also observed mortality as a result of soil heaving.

Leaf smothering.--Smothering of seedlings by annual leaf accumulation may be the most important cause of mortality where herbs, shrubs, and hardwoods are prevalent (Koroleff 1953, 1954; Rowe 1955; Gregory 1966). Under a mature 80-year-old paper birch stand in Alaska, four growing seasons passed before seedlings were large enough to avoid being crushed or smothered by leaves (Gregory 1966). Gregory concluded "...it appears very unlikely that more than an occasional white spruce can become naturally established beneath a birch stand such as this." Rowe (1955) found that the period of greatest mortality during the first 3 years after germination was from September to May and that much of this mortality was traced directly to smothering by poplar leaves. He suggested that in scarified areas a high, plowed ridge would help reduce smothering because the ridge would remain free of leaf accumulation for a long period.

Animal damage.--Browsing of white spruce seedlings by rabbits has been observed in western Canada during the peak of the rabbit cycle (Rowe 1955). Damage was confined mostly to aspen-covered or brushy areas; little or none was observed on open burns. Rodent damage such as girdling by bark-stripping has also been reported (British Columbia Forest Service 1961). Trampling of seedlings by elk has also been cited as an important cause of mortality at Riding Mountain in Manitoba (Waldron 1966).

Date of germination.--The results of a 4-year study reported by Waldron (1966) showed that slightly more 4-year-old seedlings were formed from June germinants than from July germinants and four times more than from August germinants.

LOGGING AND FIRE

From the previous discussion it can be concluded that the optimum conditions for successful regeneration of white spruce in the boreal forest

consist of the presence of a mineral soil, or at least a mixed, humus-mineral soil, seedbed; some degree of shade, particularly for germination and initial survival; an adequate white spruce seed supply; and a reduction in the density of competing vegetation. In the boreal forest region, logging and fire have been and will continue to be the principal site disturbances preceding the establishment of a new forest. The success or failure of white spruce reproduction will depend on the conditions created by these disturbances.

Logging

Logging of the relatively even-aged white spruce stands in interior Alaska is determined by economic considerations, but is probably best considered as diameter-limit cutting. The residual stand is of variable density and composed of spruce less than 10 to 12 inches in diameter and all of the hardwood component which was present prior to logging.

Little ground disturbance and mineral soil exposure occur in logged areas in this region for one or a combination of the following reasons: (1) There is a thick organic matter layer, (2) equipment which can cause the most ground disturbance is not always used, (3) the ground surface is frozen and snow covered for a large part of the year, and (4) all of the trees are not harvested, consequently much of the ground surface is not subjected to the possibility of disturbance by equipment. In the most heavily cut pure spruce stand in which yarding was accomplished with a small tractor in the summer, mineral soil was exposed on only 2 percent of the area. The unincorporated organic matter was disturbed over 18 percent of the area without exposing mineral soil.

Although Candy (1951) reported favorable reproduction following logging of old-growth stands in the Maritime Provinces, the majority of information indicated that even the most fully mechanized logging operations do not create sufficient disturbance and exposure of mineral soil (e.g., Candy 1951; Blyth 1955; Rowe 1955; Quaite 1956; Glew 1963; Prochnau 1963; Wagg 1964b; Scott 1966; Waldron 1966; Jarvis et al. 1966; Hughes 1967). The situation was summarized by Weetman (1958): "At best reliance on logging disturbance for seedbed preparation of cutovers is a haphazard arrangement which usually results in the effective scarification of only a small percentage of the cutover in an irregular fashion. Its use is generally restricted to summer mechanical logging operations on sites with a shallow humus cover."

Fire

Fire is a common natural occurrence in Alaska and other northern interior forest regions. There are numerous records of extensive fires and it appears that most areas have been burned repeatedly. As described by Lutz (1956), forests of the north are especially susceptible to destruction by fire. He mentions relatively low precipitiation, long hours of sunshine during the summer, and remarkably high air temperatures as "factors increasing the hazard in forests which, by their very nature, are readily flammable."

EFFECT OF FIRE ON WHITE SPRUCE

Most tree species of the boreal forest, especially white spruce, are easily killed by fire. In Alaska, living spruce with fire scars are uncommon and, when encountered, are almost invariably located at the extreme edge of burned areas where the intensity of the fire was low (Lutz

1956). The absence of mature trees in large burns means that, unless regeneration can be accomplished from seed already formed, no white spruce seed source would be available for immediate regeneration.

Successful establishment of spruce reproduction subsequent to severe burning has been noted in the Mixedwood Region of Manitoba and Saskatchewan (Rowe 1955; Phelps 1948), in Alberta (Candy 1951), in Alaska (Lutz 1956), and in Ontario (Scott 1966). Most of the benefits derived from burning probably accrue from destruction of organic matter and consequent exposure of a mineral soil seedbed.

Adverse effects of fire-prepared seedbeds on germination and seedling establishment have been reported. Rowe (1953a), working in southern Manitoba, found that germination on severely burned plots was about 1-1/2 months later than that on severely scarified plots; seeds on the burned plots did not germinate until late summer. Crossley (1955b) and Muri (1955) observed lower stocking of spruce on burned areas in the subalpine regions of Alberta and British Columbia, respectively. In a laboratory experiment, Muri reported that ashes had little effect on germination of Englemann spruce, but that seedling survival on ash-covered seedbeds was about one-half of that on the unburned surface due to damping off. Lutz (1956) stated that, in Alaska, as a result of repeated severe fires, productive forest land may become essentially treeless, supporting herbaceous or shrub communities. Austin and Baisinger (1955) and Tarrant (1956) have reported adverse effects of slash burning on Douglas-fir regeneration.

EFFECT OF FIRE ON SITE CONDITIONS

The effect of fire on site conditions will depend on the site, the intensity of the fire, and the frequency of fire occurrence. One of the more important site variables, with regard to spruce regeneration is the thickness and condition of the organic layer at the time of burning. In commercial white spruce stands, this layer is generally thick (2 to 5 inches), but in stands composed primarily of hardwoods it is relatively thin.

In severe fires, organic layers may be entirely consumed, exposing an altered mineral soil surface. Moist subsurface layers of organic matter usually persist after severe fires, but may be consumed by repeated burning. It was noted by Rowe (1955) that fires almost always consume the entire humus layer over well-drained, light-textured soils, but this occurs less often over moist clays. Lutz (1956) observed complete destruction of unincorporated organic matter most frequently on well-drained, rocky slopes or ridges and around the bases of spruce trees where the forest floor was dry because of interception of precipitation by the crowns. He also noted that destruction of the forest floor to mineral soil varied from 0 to 100 percent in different fires and on different areas within a given burn. His examination of recent burns indicated that deep burning to mineral soil involved about 30 to 40 percent of the surface, even in fires severe enough to kill all trees. Fires are usually most severe in pure conifer stands, becoming less severe as the hardwood component increases.

When organic layers are destroyed and their insulating effect is removed, higher soil temperatures occur within the mineral soil during summer months and soils thaw earlier in the spring and freeze earlier in the fall. In areas where permafrost occurs, the permanently frozen layer is extended downward (Lutz 1956). When the organic layer is not completely destroyed, the increased insolation due to the loss of the forest canopy can cause high surface temperatures because of the blackened, poor conducting surface.

Physical and chemical properties of the soil are altered by fire. A general summary of the findings of several studies is presented. Although study conditions are not comparable, the results indicate some general trends.

1. The total amount of nitrogen on the site decreases after burning (Austin and Baisinger 1955; Uggla 1958; Knight 1966). However, burning may increase the N in the residual material and surface soil (Knight 1966; Zwolinski 1967). Tarrant (1956) reported that light burning stimulates nitrification but severe burning strongly reduces N content of the soil.

Heilman (1966) found that nitrogen, expressed on a volume basis, increased with depth in sphagnum soils (i.e., as mineral soil is approached). He concluded that destruction by fire of the nitrogen deficient moss layers, overlying the layers of relatively high nitrogen content, helps to explain the improvement in productivity and nitrogen availability after burning of sphagnum-dominated forests of interior Alaska.

2. Austin and Baisinger (1955), Tarrant (1956) and Uggla (1958) reported that the available supply of nutrients (phosphorus, potassium, calcium, and magnesium) increased immediately following burning. However, these increases are probably only temporary as these salts may be leached out rapidly (Austin and Baisinger 1955, Uggla 1958; Scotter 1963).

3. Soil acidity is generally decreased by fire (Lutz and Chandler 1946). Scotter (1963) found decreased acidity at 1 and 3 inches in soils on burned-over land. Austin and Baisinger (1955) reported that pH had decreased after 2 years but it had not returned to the preburn level. Tarrant (1954) found that the effect of fire on pH and the rate of change in soil pH following burning was related to severity of burns; the harder the burn the greater the rise of pH and the less rapid the return to normal. Uggla (1958) found that in northern Swedish forests, 25 years passed before pH values were equal to those in unburned areas.

4. Severe burning reduced pore volume and percolation rate below levels in unburned soil (Tarrant 1956). Scotter (1963) reported reduced infiltration rates in a 13-year-old burn, but because of a small number of samples he was unable to draw any definite conclusions.

5. Scotter (1963) reported that soil temperatures at depths of 1 and 3 inches were significantly higher in 5-, 13-, and 22-year-old burns than in unburned areas.

The residual effects of fire may persist for relatively long periods of time in the dry interior of Alaska as Scotter (1963) and Uggla (1958) found for northern Saskatchewan and northern Sweden, respectively.

SILVICULTURAL CONSIDERATIONS

Seedbed Scarification

Because logging and fire do not often result in conditions optimal for the establishment of white spruce, scarification has been used to prepare a seedbed and reduce the density of competing vegetation. Scarification has been shown by a number of investigators to greatly improve seedbed conditions (e.g., LeBarron 1945; Phelps 1948; Crossley 1955a, 1955b; Parker 1952; Blyth 1955; Place 1955; Rowe 1955; Quaite 1956; Ackerman 1957; MacLean 1959; Jeffrey 1961; Lees 1962, 1963, 1964a; Prochnau 1963; Wagg 1964; Gilmour and Konishi 1965; Gilmour 1966; Jarvis et al. 1966; Waldron 1966; Scott 1966; Hughes 1967). The success of this treatment will, however, vary between sites and between years on the

same site (Jarvis et al. 1966, Scott 1966; Waldron 1966). Scarification equipment, methods, and guidelines have been discussed by Weetman (1958), Decie and Fraser (1960), Gilmour and Konishi (1965), Scott (1966), Gilmour (1966), Jarvis et al. (1966), Waldron (1966), and Hughes (1967). The report by Gilmour (1966) of the success of winter scarification followed by seeding may be particularly applicable to interior Alaska conditions.

In the past, scarification has not been widely practiced. This was due to the high cost of treatment, to unfavorable economic conditions, and to disregard of logged and burned areas. The increasing desire to obtain regeneration immediately after harvesting and to regenerate inadequately stocked, burned, and cut areas has made this treatment more common in recent years. For example, in British Columbia (the Prince George Forest District), scarification acreage has increased from 243 in 1956 to 10,000 in 1964. The total area treated up to and including 1964 has been 37,700 acres (Gilmour and Konishi 1965).

The length of time the scarified seedbed remains receptive is important, particularly if natural seedfall, with its inherent annual variation, is relied upon to regenerate a specified area. Most observers report that, depending on site, seedbeds are most receptive for a period of from 3 to 5 years following treatment (Rowe 1955, Crossley 1955a, Lees 1964a, Hughes 1967). A detailed study of this problem in British Columbia reported the following (Arlidge 1967):

1. Scarified areas should be seeded the same year and not later than one growing season after treatment.

2. The size of the seedbed has an important effect; success was lower on small seedbeds than large.

3. Large tractors did a significantly better job than medium or small machines. This was related to the creation of more large seedbeds on areas scarified by large tractors.

Several problems have arisen in connection with use of the treatment. Although they are probably not always important or critical they must be recognized. Depending on the soil type, compaction may result in poorer growth in portions of the treated area. Hughes (1967) and Lees (1964b) report that water retained in depressions created during scarification may reduce seedling growth or cause mortality due to flooding. Lees reported the results of a laboratory experiment which showed that 2-year-old seedlings were more tolerant to immersion than those 1-year-old, and that all 1- and 2-year-old seedlings died after 14 days' immersion. He also found that periods of repeated immersion (3-1/2 to 10-1/2 days) shorter than 14 days had cumulative effects which also resulted in mortality.

Prescribed Burning

The use of fire as a silvicultural tool is important and is increasing in importance in the southeastern United States, the Lake States, Canada, and northern Europe. Because of the role fire has played in forest succession in Alaska and because of its relatively low cost of application, its use should be seriously considered. It is possible that, if the proper burning conditions exist, fire by itself can create an adequate seedbed for spruce regeneration. However, Jarvis and Tucker (1968a, 1968b) concluded that fire alone was not a satisfactory seedbed treatment at the Riding Mountain Experimental Area. They suggested that seedbed treatments combining scarification and burning may prove the most desirable. Effective use of prescribed fire requires data on the effect of fire on site factors and correlation of fire intensity with fuel moisture, fuel type, and weather conditions.

Seed Supply

Even if there is a suitable seedbed, a scarcity of seed may pose an obstacle to regeneration. In selectively logged areas, seed abundance will depend on the quality of the residual trees and their distribution. Waldron (1965) has reported that dominants and codominants produced more cones than intermediate and suppressed trees. Even in heavy seed years, trees in the latter two crown classes produced light seed crops.

In clearcuts, the distance from the uncut forest is of primary importance. The distance of spruce seed dispersal varies with wind, weather, and stand conditions. Some values for this distance have been reported. Rowe (1955) found that 330 feet was the greatest measured distance traveled by seeds, but he stated that seed could be blown farther. MacLean (1959) suggested that clearcut areas be restricted to about 200 feet in width. Hughes (1967) found that seed dispersal in Ontario was not adequate in the middle of a 660-foot-wide clearcut block, and he recommended clearcut strips up to 400 feet wide. The importance of seed blown over snow-covered surfaces depends on the amount of seed shed late in the year. This may not be of major importance in regenerating white spruce. In both clearcuts and selectively logged areas, the quantity of seed produced in a given year will also be important.

The average number of seeds required to establish a seedling varies with site and seedbed. Eis (1967b) reported that, in the Prince George Forest District, one seedling became established for each seven to nine viable seeds on mineral soil, whereas 800 to 1,000 seeds were required on litter. Prochnau (1963), also working in British Columbia, found in a drier than average year that eight viable seeds (protected against rodents) produced one seedling whereas in a wetter than average year four seeds produced one seedling. He concluded that 10 seeds (protected against rodents) per spot are necessary to produce satisfactory results under any conditions. Scott (1966) reported that in Ontario, it is a common practice to use 20,000 seeds per acre when seed is broadcast and six to twelve seeds per spot in spot seeding. These operations are generally conducted on scarified areas and the seed is protected against rodents.

Seed years are generally classified as good, medium, or poor, or by similar adjectives. The adequacy of the quantity of seed during so-described years has been reported. Jarvis et al. (1966) reported that there is seldom a scarcity of white spruce seed in the Mixedwood Forest Section. For Alberta, Quaite (1956) concluded that good seed years do not appear to be necessary to obtain satisfactory stocking of white spruce if a sufficient number of standing stems are left on an area. He reported excellent reproduction after scarification of clearcuts in a medium to good seed year and inadequate reproduction in a light seed year. In the subalpine region of Alberta, Crossley (1955b) found that, if the most receptive seedbed received seed during a light seed year and the seed was subject to normal seed loss, it did not produce a stand that would meet minimum stocking standards 5 years after germination. Because of this he suggests that only a heavy seed crop will satisfy the demands made by forest fauna and still leave enough seed for regeneration. Preliminary data on seed production in interior Alaska indicate that seed production during some years is definitely not adequate for regeneration.

Artificial Regeneration

Although natural regeneration has been and may continue to be the sole means of regenerating white spruce in Alaska, artificial seeding and planting are important means of regeneration in other parts of the boreal forest.

Artificial seeding, accomplished by either broadcast or spot seeding, provides a means of assuring an adequate quantity of seed in an area at any time. However, it is relatively expensive; it requires collection of seed from mature stands and the handling and storage of large amounts of seed. It is not always reliable and successful and, in some cases, seeding has to be repeated. Broadcast seeding does not guarantee that all of the seed will land on a receptive seedbed, and it will probably only be successful following scarification. Parker (1952) concluded that artificial seeding, although producing a greater number of seedlings and earlier regeneration, was of little practical importance and not commensurate with the cost of the operation. This conclusion is questionable with regard to its general applicability.

The destruction of seed by small mammals and insects must be given consideration when artificial seeding is to be used. For example, Radvanyi (1966) found that of 2,000 hybrid white spruce seed, coated with an insecticide and sown in June, 49 percent were destroyed (35 percent by mice, 9 percent by chipmunks, 3 percent by shrews, and 2 percent by insects). Gregory (1966) has reported seed losses believed due to small mammals in Alaska. To reduce these losses seed can be treated with animal repellents such as endrin and Arasan (Prochnau 1963; Scott 1966; Cayford and Waldron 1966).

Planting white spruce seedlings instead of, or in addition to, direct seeding has been suggested, particularly for good sites (Glew 1963; Eis 1966; Hughes 1967; Arlidge 1967). Some of the advantages of planting are that selected genotypes can be used, spacing can be regulated, collected seed is used more efficiently than in artificial seeding operations, the critical periods of germination and initial survival under uncontrolled conditions are bypassed, and the older seedling is better able to compete with fast-growing, herbaceous, and woody vegetation. Because of the rapid growth of competing vegetation on good sites, scarification is desirable. Planting is expensive and is probably of little practical importance in extensive forestry except on extremely good sites. Planting and direct seeding will probably become more important with increasing intensity of management in the boreal forest.

Silvicultural Systems

The applicability of the common silvicultural systems to even-aged spruce management depends upon the conditions created by the system and their suitability for spruce regeneration. Optimum conditions for natural regeneration of spruce have been discussed. In general, they consist of the presence of a mineral soil seedbed, partial shade with not less than 20 percent of full light, an adequate source of seed, and elimination of competition for soil water and light.

Lees (1962, 1963, 1964a), Glew (1963), and Waldron (1966) have concluded that the silvics of spruce suit it to management under a two-cut shelterwood system. For the spruce-aspen stands of Alberta, Lees recommended that the first cut should occur at about age 95 and that it remove up to 60 percent by volume. Seedbed scarification follows the first cut and the overstory should be removed at age 120. This is considered

rotation age in these stands. For stands similar to those at the Riding Mountain Experimental Area, Waldron (1966) suggested a residual stand of 40 to 60 square feet basal area per acre. If possible, the stand should be entirely of spruce but there should be no less than 25 square feet of this species. The balance of the stand would be hardwoods. It is important that the residual spruce be from the dominant and codominant crown classes; these are the best seed producers. As much as possible of the hardwood component should be harvested or poisoned to reduce spruce seedling mortality by crushing. The first cut should be followed by scarification; the second cut would follow seedling establishment. Under the shelterwood system the seedbed treatment must be mechanical, as prescribed burning will kill the residual stand. Increased growth of the residual stems, as a result of release, may make this system desirable in Alaska where sawlog production is, at present, the primary goal. However, too much blowdown and the high cost of the second cut are disadvantages.

Hughes (1967) recommended clearcutting in blocks or strips 330 to 400 feet wide with scarification 2 or 3 years after cutting. Burning and mechanical seedbed preparation are both possible under this system. Direct seeding and planting may be desirable following clearcutting. The advantages of this system would be most fully realized in those areas where utilization is more complete.

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